UNCLASSIFIED

AD NUMBER
ADB006655
LIMITATION CHANGES
TO: **Approved for public release; distribution is unlimited.**
FROM: **Distribution authorized to U.S. Gov't. agencies only; Test and Evaluation; SEP 1975. Other requests shall be referred to Space and Missile Systems Organization, Attn: DYJB, PO Box 92960, Worldway Postal Center, Los Angeles, CA 90009.**
AUTHORITY
USAF ltr, 30 Apr 1981

THIS PAGE IS UNCLASSIFIED

AEDC-TR-75-68

MIRROR SCATTER MEASUREMENTS FACILITY COMPARISON

VON KÁRMÁN GAS DYNAMICS FACILITY
ARNOLD ENGINEERING DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
ARNOLD AIR FORCE STATION, TENNESSEE 37389

September 1975

Final Report for Period August 12, 1974 – March 5, 1975

Distribution limited to U.S. Government agencies only; this report contains information on test and evaluation of military hardware; September 1975; other requests for this document must be referred to Space and Missile Systems Organization (DYJB), PO Box 92960, Worldway Postal Center, Los Angeles, California 90009.

Prepared for

SPACE AND MISSILE SYSTEMS ORGANIZATION (DYJB)
PO BOX 92960, WORLDWAY POSTAL CENTER
LOS ANGELES, CALIFORNIA 90009

NOTICES

When U. S. Government drawings specifications, or other data are used for any purpose other than a definitely related Government procurement operation, the Government thereby incurs no responsibility nor any obligation whatsoever, and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise, or in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Qualified users may obtain copies of this report from the Defense Documentation Center.

References to named commercial products in this report are not to be considered in any sense as an endorsement of the product by the United States Air Force or the Government.

APPROVAL STATEMENT

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

Jimmy W. Mullins

JIMMY W. MULLINS
Lt Colonel, USAF
Chief Air Force Test Director, VKF
Directorate of Test

Frank J. Passarello

FRANK J. PASSARELLO
Colonel, USAF
Director of Test

UNCLASSIFIED

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AEDC-TR-75-68	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) MIRROR SCATTER MEASUREMENTS FACILITY COMPARISON		5. TYPE OF REPORT & PERIOD COVERED Final Report - August 12, 1974 - March 5, 1975
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) R. P. Young - ARO, Inc.		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Arnold Engineering Development Center (XO) Arnold Air Force Station Tennessee 37389		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS Program Element 63424F System 641A
11. CONTROLLING OFFICE NAME AND ADDRESS Space and Missile Systems Organization (DYJB), P. O. Box 92960, Worldway Postal Center, Los Angeles, California 90009		12. REPORT DATE September 1975
		13. NUMBER OF PAGES 53
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A

16. DISTRIBUTION STATEMENT (of this Report)

Distribution limited to U.S. Government agencies only; this report contains information on test and evaluation of military hardware; September 1975; other requests for this document must be referred to Space and Missile Systems Organization (DYJB), P. O. Box 92960, Worldway Postal Center, Los Angeles, California 90009.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Available in DDC

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

optical surface quality
mirror surfaces
contamination
particulate materials
scatterometers
lasers

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A "Round-Robin" mirror scatter measurements program was conducted for the purpose of comparing scatter measurement equipment and data reduction techniques employed by several IR sensor manufacturers. Measurements of mirror scatter by each of the participating facilities using the same test mirrors was found to be in general agreement. No significant differences in data reduction techniques used by the different participants were discovered.

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

PREFACE

The work reported herein was conducted by the Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), at the request of the Space and Missile Systems Organization (SAMSO), under Program Element 63424F, System 641A. The results of the tests were obtained by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), under ARO Project No. V42P-24B (VC522). The author of this report was R. P. Young, ARO, Inc. Data reduction was completed on March 7, 1975, and the manuscript (ARO Control Number ARO-VKF-TR-75-34) was submitted for publication on March 24, 1975.

CONTENTS

ILLUSTRATIONS

TABLES

1.0 INTRODUCTION

The ability of an IR sensor to detect a low radiance source in the presence of an intense off-axis source is limited, in part, by the energy scattered from the sensor primary mirror. To predict the performance for a reflecting telescope, the scattering characteristics of the mirrors must be known. Telescope manufacturers generally measure the scattering characteristic of the mirrors used in their products. Different telescope manufacturers used different types of scatterometers to make scatter measurements, and data reported by one manufacturer has sometimes been considerably different from data reported by another even though they were testing mirrors of the same manufacturing state of the art. For this reason, it was decided that a "Round-Robin" program be conducted to allow comparison of equipment and data reduction techniques employed by several telescope manufacturers. Mirrors of differing quality were purchased, and were taken to each participant for measurement.

Those included in this program were: (1) Honeywell Radiation Center (HRC), (2) Aerospace Corporation, (3) Rockwell International (RI), (4) Hughes Aircraft, Inc., (5) Naval Weapons Center (NWC), China Lake, California, (6) Perkin-Elmer Corporation (PE), and (7) Honeywell Systems and Research Center (HS&RC). Addresses and contacts at these facilities are presented in Table 1.

2.0 SCATTEROMETERS

The scatterometers, which are used to make bidirectional reflectance distribution function (BRDF) measurements at the different facilities, are described in the following sections.

2.1 ARNOLD ENGINEERING DEVELOPMENT CENTER (AEDC)

The AEDC 10.6-μ scatterometer (Ref. 1) is presented in Fig. 1. The system consisted of a 3-w CO_2 laser, 16-Hz chopper, beam attenuator, 1.25-cm-diam aperture, collection telescope with detector, and an angular position readout. The laser operated single mode (TEMooq) and was polarized in the vertical plane. Beam power distribution was Gaussian, and the effective beam diameter at the test mirror was nominally 1 cm (1/e power points). Beam attenuation ($T = 2.2 \times 10^{-5}$) was needed when

on-axis measurements were made. A He-Ne laser beam was aligned paraxial to the CO_2 laser beam after reflection from the germanium window. This permitted visual location of the IR beam for system alignment.

The 1.25-cm-diam aperture was mounted at a distance from the test mirror such that its image was formed at the telescope lens. Energy scattered by optical elements up-stream of this aperture and striking the test mirror was focused through the aperture image.

Scattered energy from the test mirror was measured with an IR radiometer. The radiometer consisted of a 6.4-cm focal length germanium lens, telescope barrel, and a 1-mm square pyroelectric detector. The lens was focused so that the detector was imaged at the mirror surface. A field stop was placed in front of the lens limiting the collection optics field of view to 28 by 19 mrad. The radiometer was mounted on a motor driven two-axis gimbal, which was mounted in an arm that pivots about the front surface of the test mirror. Angular arm position was measured with a resolver and digital angle readout. Detector voltage was measured with a lock-in amplifier.

Test mirrors were mounted on a two-axis gimbal. The gimbal could be translated in two directions to allow scatter measurements at different areas on a mirror surface. A 3.8-cm hole in the center of the gimbal was provided so that the laser beam could pass through the mirror holder during stray radiation testing.

The AEDC, 0.6328-μm scatterometer was essentially the same as the 10.6-μm scatterometer as shown in Fig. 1. The alignment He-Ne laser was installed in place of the attenuator box and the germanium window removed. The IR radiometer was replaced with a 0.6328-μm radiometer. It consisted of a glass lens (5-cm-diam, 100-mm focal length) and a silicon detector (5-mm square). A 5- by 2.5-cm field stop was placed in front of the lens to limit the field of view to 64 by 32 mrad. A current mode preamplifier and lock-in amplifier was used to measure the cell current.

2.2 HONEYWELL RADIATION CENTER (HRC)

The HRC, 10.6-μm scatterometer (Fig. 2) is similar in design to the AEDC scatterometer. It consisted of a 3-w CO_2 laser, attenuator box, chopper, aperture, and radiometer. The radiometer was made of

a 2.54-cm focal length lens, telescope barrel, and a 0.51- by 0.43-mm HgCdTe detector. Detector voltage was measured with a lock-in amplifier. A 7.94-mm-diam field stop was placed over the lens to limit the collection solid angle to 1.1×10^{-4} sr. The radiometer was mounted on an arm that pivoted about the front surface of the test mirror. A two-axis gimbal was used to align the radiometer to the test mirror. Angular arm position was measured with a mechanical scale and pointer system. The aperture was positioned too close to the test mirror, and its image was, therefore, formed some distance behind the radiometer.

The test mirror holder was made of several translation stages. No gimbal motion for the test mirrors was provided. The test mirror was mounted directly to the vertically oriented translation stage. This stage presented a rather large reflective surface when testing small diameter mirrors. There was no hole through the stage to allow the laser beam passage; therefore, tests to measure stray radiation from the mirror support cannot be performed.

2.3 ROCKWELL INTERNATIONAL (RI)

The RI scatterometer is shown in Fig. 3. The RI scatterometer was normally set up to test large diameter mirrors, and it had not been used in quite a long time. It consisted of a 350-w CO_2 laser, chopper, aperture, radiometer, and indexing head to hold the mirror. The radiometer was mounted to an arm which was rotated with the indexing head. A shimming technique was used to align the radiometer to the test mirror; no gimbals were available. This was normally acceptable because the radiometer had a relatively large field of view (approximately 4 deg). Radiometer output was measured with a lock-in amplifier, and radiometer angle was measured from the angle scale on the indexing head. The radiometer had a 4.76-mm entrance aperture, relay optics, and a cryogenically cooled detector. Its collection solid angle was nominally 8×10^{-6} sr when placed 63.5 cm from the test mirror.

During early tests, it was determined that the large diameter of the laser beam, in conjunction with the large field of view of the radiometer, did not permit measurement of the small diameter Round-Robin mirrors. Radiation from the mirror holder and mirror edge was greater than that from the mirror surface. (This problem does not exist when testing larger mirrors.) The 350-w CO_2 laser was replaced by a 6-w CO_2 laser which had a smaller beam diameter. It was also placed much

closer to the test mirror. A small mirror holder was designed which allowed the laser beam to pass through the center of the holder (no mirror installed), thus permitting stray radiation measurements. The major problem encountered by changing lasers was that the dynamic range of the scatter measurement apparatus was reduced. The lowest BRDF that could be measured was approximately 2×10^{-5} sr^{-1} (detector noise limit).

2.4 AEROSPACE CORPORATION

The Aerospace scatterometer presented in Fig. 4 was very much like the AEDC scatterometer. It consisted of a 10-w CO_2 laser, aperture, 13-Hz chopper, and a radiometer. An He-Ne laser beam was reflected from the front Brewster window of the CO_2 laser and was aligned coaxially to the CO_2 laser beam. The He-Ne beam was used for system alignment and provided a reference for locating the specularly reflected beam from the test mirrors.

The radiometer consisted of a 12.7-cm focal length lens, telescope barrel, and a 1-mm square pyroelectric detector. Detector voltage was measured with a lock-in amplifier. The detector responsivity was about 2 orders of magnitude below the manufacturer's specification. Collection solid angle of the telescope was nominally 5.4×10^{-4} sr. The radiometer was mounted on a two-axis gimbal, which was mounted on an arm that pivoted about the front surface of the test mirror. Angular arm position was measured with a potentiometer and DVM, or from the scale scribed on the indexing head used to rotate the radiometer arm.

Test mirrors were mounted on a two-axis gimbal, that could be translated across the laser beam in the horizontal plane. The hole in the mirror mount was not large enough to permit stray radiation measurements of the mirror holder assembly.

2.5 HUGHES AIRCRAFT

The Hughes scatterometer was designed for making BRDF measurements at several wavelengths between 0.638 and 10.6 μm. Several different laser sources are used to provide energy at the different wavelengths. Measurements were only made at 10.6 μm for the Round-Robin program; therefore only the CO_2 laser source is shown in the schematic

diagram of the Hughes scatterometer (Fig. 5). Mirror M-2 was placed into the optical path for scatter measurements using the CO_2 laser. The HeNe laser was used for system alignment (mirror M-2 removed).

Aperture AP-1, just in front of the toroidal mirror (M-3), was 12.5 mm in diameter. The laser beam was focused by the 29-cm focal length toroidal mirror, through aperture AP-2 (5-mm diam), and expanded to the 20-cm-diam, 152-cm focal length spherical mirror (M-4). The beam converged to the test mirror and focused onto scanning detector D-1 (HgCdTe, 2 by 2 mm square). No collection optics were used. The detector was mounted on an arm that pivoted about the front surface of the test mirror. Angle measurements were made from a scale on the indexing head turntable. Collection solid angle depended on the focal length of the test mirror. Collection solid angles for the flat and 64-cm focal length mirrors were 1.6×10^{-5} and 4.4×10^{-5} sr, respectively.

Detector D-2 was used to monitor laser power reflected from the chopper. Output from both detectors was measured with lock-in amplifiers. The scanning detector output was ratioed to the laser power monitor, and the ratio voltage was measured with a DVM.

The test mirror mount was designed to minimize the area viewed by the detector. A rod, attached to the back of the test mirror, was held in a small clamp, centering the mirror in the illuminated area. The mirror mount was easily removed, allowing the scanning detector to be swung 180 deg from its normal position. In this position, stray radiation measurements could be made so that minimum measurable BRDF data could be calculated. Beam diameter at the test mirror location was nominally 15 mm.

2.6 NAVAL WEAPONS CENTER (NWC) OPTICAL EVALUATION FACILITY

The NWC Optical Evaluation Facility (Fig. 6) was designed to measure total scatter and BRDF from mirror surfaces up to 40 cm in diameter. Details of the system are presented in Refs. 2 and 3. Measurements can be made at discrete wavelengths between 0.3507 μm and 10.6 μm. Several lasers are required to cover this wavelength interval. Only the CO_2 and Krypton lasers were used for the Round-Robin measurements. The laser to be used was selected by a sliding aperture and fixed mirror assembly, which is diagramatically represented as a rotating mirror (M-2) in Fig. 6. The 81-cm focal length mirror (M-7, Fig. 6)

converged the CO_2 laser beam, reducing the beam diameter at the test mirror.

Several apertures, not described in Refs. 2 and 3, were in the system at the time of the Round-Robin measurements. One was located at the CO_2 laser (AP-1, 6-mm diam), one was placed just before the Coblentz collector (AP-2, 2.69-mm diam), and one was placed in front of the test mirror (AP-3, 4.95-mm diam). The specularly reflected beam from the test mirror did not pass through aperture AP-2.

Several detectors were used for the measurements. Total scattered energy was collected by the Coblentz sphere and focused on Detector D-1. Detector D-2 measured the energy reflected from the test mirror and was used for reflectivity measurements. Detector D-3 was used to monitor laser output power, and Detector D-4 was used to measure energy for BRDF calculations. Detector D-4 was mounted on an arm which pivoted about the test mirror surface, at a distance of 9.8 cm. The scanning detector (D-4) was a 2 by 0.5-mm pyroelectric, with no collection optics. Collection solid angle was 1.16×10^{-4} sr.

All of the detector voltages were measured with lock-in amplifiers. The total scatter detector (D-1) and the scanning detector (D-4) voltages were ratioed to the laser monitor detector (D-3) voltage. The ratio voltage was measured with a DVM.

The test mirror was mounted on a Leitz optical dividing head, whose axis was accurately aligned with that of the system. Mirrors were positioned relative to the Coblentz sphere using a fiber optics positioning device. The dividing head could be translated along the optical axis, away from the Coblentz sphere, so that Detector D-4 could be rotated 180-deg for stray radiation measurements.

2.7 HONEYWELL SYSTEMS AND RESEARCH CENTER (HS&RC)

The HS&RC scatterometer is presented in Fig. 7. It consists of a 5-w CO_2 laser, 141-Hz chopper, and radiometer. The radiometer was made using a 42-cm focal length, 10-cm-diam, spherical mirror and a 3.2-mm square HgCdTe detector. The detector was positioned at the collecting mirror focal length. The detector holder was designed to allow for CaF_2 attenuators to be stacked in front of the detector. A folding mirror (not shown in Fig. 2), located just behind aperture AP-2, folded the beam up to the detector. This was required because the

detector dewar had to be mounted vertically. Detector voltage was measured with a lock-in amplifier. The radiometer assembly was mounted on an arm that pivoted about the front surface of the test mirror. Angular arm position was measured with a mechanical scale and pointer system.

Test mirrors were mounted on a two-axis gimbal that could be translated horizontally and vertically. The hole in the mirror mounting hardware was not large enough to allow for stray radiation measurements of the mirror holder assembly.

Two apertures were installed in the scatterometer for the first mirror BRDF measurement. A third aperture was added later. Aperture AP-2 was positioned about 11 cm in front of the detector, just in front of the detector folding mirror. This aperture was nominally 4-mm in diameter. The second aperture was the exit hole of the chopper enclosure. It was nominally 13 mm in diameter and was about 61 cm from the test mirror. This was an unfortunate location for mirror scatter measurements for the Round-Robin mirrors. Stray radiation emitted from the chopper enclosure aperture would not be converging after it reflected from the test mirrors. This radiation would be directed to the detector along with the scattered radiation from the test mirror surface, for the near specular BRDF measurements.

A third aperture was added to the system after the first mirror measurement was made. This aperture was nominally 13-mm in diameter and was placed on the 10-cm-diam collecting mirror holder. This reduced the radiometer angular movement required to block the specular reflection from the test mirror surface. Only a small reduction of detector signal resulted from the reduction of collecting mirror area because the radiometer was focused at infinity and it was viewing a small diameter source.

2.8 PERKIN-ELMER (P-E)

The Perkin-Elmer scatterometer is shown in Fig. 8. A 4-w CO_2 laser (3-mm beam diam) was used as the radiation source. The CO_2 beam passed through a 6.4-mm-diam aperture (AP-1) and the chopper (4320 Hz) before it was focused by the 12.7-cm focal length toroidal mirror (M-1) at the plane of aperture AP-2 (1.5-mm diam). The holes in the chopper disc were only 4.8-mm in diameter, and at the 45-deg

chopper angle, the holes represented an elliptical aperture of 4.8 by 3.4 mm to the laser beam. The expanding beam then passed through apertures AP-3 (3.2-mm diam) and AP-4 (13-mm diam). The beam converging mirror (M-2) was placed at a distance slightly less than its radius of curvature (100 cm) from aperture AP-2, directing a convergent beam onto the mirror under test. The beam profile at the test mirror was elliptical, with a maximum diameter of about 10 mm.

An HgCdTe detector, cooled to 77 K, measured the level of scattered radiation. A small mirror (M-3) folded the scattered energy onto the 2-mm square detector. The detector, mirror M-3, and a preamplifier (Gain = 100) were mounted on an arm whose axis of rotation was in the plane of the test mirror surface. Angle measurements were made from a scale scribed on the indexing head, onto which the radiometer arm was mounted. Collection solid angle of the detector depended on the focal length of the test mirror. Collection solid angle for the flat and 64-cm focal length mirrors were nominally 6.5×10^{-5} and 9×10^{-5} sr, respectively.

Test mirrors were attached to a rod support by a 1/4-20 stud. The rod was then held by a support structure which would be adjusted so that the mirror was centered in the CO_2 beam. The mirror mount was easily removed, allowing the scanning detector to be swung 180 deg from its normal position. In this configuration, stray radiation measurements could be calculated. The detector was rotated 90 deg in its mount, and mirror M-3 was removed for the stray radiation measurements.

3.0 TEST MIRRORS

Sixteen mirrors were used for the Round-Robin program. All the mirrors were nominally 2 in. in diameter and 1 in. thick. A 1/4-20 NC threaded hole was provided in the center of the rear surface for mounting. Fifteen of the mirrors had a nominal 25-in. focal length (positive), and one was flat. The mirrorswere divided into three groups; those made of beryllium, glass, and nickel plated aluminum. The letter in the mirror serial number designates the mirror base material (i.e., B-beryllium, G-glass, A-nickel plated aluminum). There were three beryllium mirrors (B-1, B-2, and B-3), three glass mirrors (G-1, G-2, and G-3), and 10 nickel-plated, aluminum mirrors (A-2, and A-5 through A-13). Serial number A-13 was a flat. All the nickel plated mirrors were "super polished" to have a very low scattering surface.

4.0 TROUBLE SHOOTING GUIDE

The major problem encountered in trying to make BRDF measurements with "super polished" mirrors is multiple reflections of stray radiation from hardware associated with the scatterometer. Stray radiation can be classed as laser energy reflected from: (1) the mirror holding fixture, (2) the rolled edge of the mirror, and (3) the radiometer housing. Laser beam spread is also a source of unwanted radiation when testing flat mirrors. The following paragraphs illustrate tests which can be performed to determine if BRDF measurements are being influenced by these sources of unwanted energy.

4.1 REFLECTIONS FROM MIRROR HOLDING FIXTURE

Lasers operating in the TEMooq mode have a Gaussian beam profile. In this mode, most of the energy in the beam is contained in a relatively small diameter, usually defined by the 1/e power points. However, a transverse scan made through the laser beam reveals that some energy is present even at large distances from the central beam. This energy can be a source of detector signal in a scatterometer because it can reflect from the mirror holding fixture, back toward the radiometer (Fig. 9a). A simple test to determine if mirror holder reflections are present is to perform a scatter measurement without a test mirror in place. A hole, smaller than the test mirrors, must be provided in the mirror holder assembly to allow the main laser beam passage. A trap must be provided to capture the main laser beam. It should be located as far as possible behind the mirror holder. System BRDF can be calculated from the radiometer signal. This BRDF represents a lower system BRDF measurement capability.

4.2 MIRROR EDGE ROLLOFF

Most mirrors tested have a rolled edge of some radius, as shown in Fig. 9b. Laser energy, as discussed in Section 4.1, reflects from this edge in directions other than that of the main beam and can be intercepted by the system radiometer. This problem can be evaluated by making a mirror BRDF measurement at a given angle, then repeating the measurement with an aperture (Fig. 9b) placed over the edge of the mirror. If the radiometer signal increases or decreases when the aperture is placed over the mirror, there is a good probability that the

mirror BRDF measurements are in error because of stray radiation from the mirror edge.

4.3 SPECULAR BEAM REFLECTION FROM RADIOMETER HOLDER

Stray radiation can be intercepted by the system radiometer by multiple reflections of the laser beam from the radiometer holder (Fig. 9c). Energy hitting the radiometer holder, reflects to the mirror holder, mirror edge radius, and from radiation shields (Fig. 9c). Inserting a small mirror in the specular beam from the test mirror, directing the beam out of the scatterometer, is helpful in determining if energy from this source is being intercepted by the radiometer. If the detector signal decreases when the mirror is inserted, stray radiation from the radiometer holder is probably a problem. The best solution is to redesign the radiometer holder so that the specularly reflected beam from the test mirror does not hit it, or anything else in the vicinity of the scatterometer.

4.4 LASER BEAM SPREAD

Beam spread can be particularly troublesome when testing flat mirrors because it affects BRDF measurements at small angles. The minimum BRDF measurement capability can be determined by making a BRDF measurement with the radiometer swung 180 deg from its normal position and making a test scan (mirror and mirror holder removed from system). This measurement provides the minimum BRDF that can be measured up to the angle that the radiometer no longer views the last aperture in the system.

5.0 DATA REDUCTION

5.1 INCIDENT POWER METHOD

The quantity that describes the angular dependence of energy scattered from an optical surface is the bidirectional reflectance distribution function (BRDF). It is defined as the spatial distribution of the ratio of scattered energy to incident energy that is observed by a detector of small angular subtense normalized to one steradian and taking into account the projected surface area viewed. For near normal incidence, the BRDF can be expressed as:

$$\mathrm{BRDF} = \frac{P_s}{P_i \, \Omega \cos \theta} \tag{1}$$

If the incident and scatter energy (P_i and P_s) are measured with the same radiometer, the BRDF can be expressed in terms of the radiometer output:

$$\mathrm{BRDF} = \frac{V_s}{V_i \, \Omega \cos \theta} \tag{2}$$

If the incident energy is determined by measuring the specularly reflected beam from the test mirror and attenuators are placed in the incident beam during the measurement, Eq. (2) then takes the form:

$$\mathrm{BRDF} = \left[\frac{T\rho_m}{V_r}\right] \frac{V_s}{\Omega \cos \theta} \tag{3}$$

The bracketed term represents the incident power measurement. Equation (3) has been used at AEDC for BRDF measurements when the apparatus is mounted within an inaccessible enclosure.

A slightly different approach to BRDF measurements has been taken at Rockwell International. A power meter is used to measure incident energy (P_i) and a radiometer to measure scattered energy (P_s). It is then necessary to calibrate the radiometer against the power meter. Calibration is accomplished by expanding the CO_2 laser beam with a positive lens. The power meter is placed as far from the lens as possible and still have an acceptable scale reading. The radiometer is placed farther from the lens, at a distance such that the maximum radiometer output is obtained. Based on this radiometer calibration, BRDF can be calculated as:

$$\mathrm{BRDF} = \frac{K \, V_s \, D^2}{P_i \cos \theta} \tag{4}$$

where V_s is measured with the radiometer, P_i is measured with the power meter, and D is the distance (cm) from the radiometer to the test mirror. The radiometer sensitivity (K) is expressed in w/cm^2 volt as determined in the above calibration. It should be noted that the above calibration assumes a uniform irradiance at the power meter and radiometer during calibration. This assumption can be invalid because the laser beam being expanded has a Gaussian profile and the power meter has a much larger collection solid angle than does the radiometer.

5.2 DIFFUSE REFLECTOR METHOD

Mirror BRDF was defined in the previous section (5.1) by Eq. (1). The basic difference in the two subsequent equations was the method used to measure the incident power on the test mirror. Another method of measuring the incident power on the test mirror, without using attenuators, is to measure the radiometer signal from the radiation reflected from a diffuse (Lambertian) reflector. The radiometer signal at near normal incidence would be:

$$V_D = \frac{\rho_D P_i}{\pi} \Omega R \tag{5}$$

or

$$P_i = \frac{V_D \pi}{\Omega R \rho_D} \tag{6}$$

The scattered power from a test mirror could be expressed as

$$P_s = \frac{V_s}{R} \tag{7}$$

Substituting Eqs. (6) and (7) into Eq. (2) gives:

$$BRDF = \frac{V_s \rho_D}{\pi V_D \cos\theta} \tag{8}$$

The problem becomes one of finding a diffuse reflector with a known reflectivity and Lambertian distribution of the reflected energy. At AEDC, the diffuser is made by spraying Nextel® 101-C10 velvet paint onto the flat side of an aluminum cylinder. After the paint is thoroughly dried, gold is deposited over the paint in a vacuum evaporator. Reflectivity of the finished diffuser was measured to 2.5 μm using a DK-2A spectrometer. It was assumed that the reflectivity at 10.6 μm was about the same as at 2.5 μm, since the reflecting surface was gold. Angular distribution of reflected energy was measured with the AEDC scatterometer.

6.0 RESULTS

All of the BRDF data presented in this report were calculated using the diffuse reflector method presented in Section 5.2. The AEDC diffuser was used for all measurements. If a facility normally uses a

different method for data reduction, the percent deviation resulting from use of their method is presented. Results are presented in two forms. The first is a graphical presentation of BRDF versus angle as measured at the participating facilities. Data presented in this form was limited to mirrors that were measured at three or more facilities.

Results of BRDF measurements made at each facility are also presented in a tabular format. Tabulated results are presented for all mirrors measured at each facility. The table for each facility includes the mirror number, the number of BRDF measurements made at different angular positions for each mirror (number of data points), and the average percent deviation. Average percent deviation was calculated for each mirror by summing the percent deviation at each angular measurement, and dividing by the number of BRDF measurements. Percent deviation was calculated by subtracting the BRDF value measured at each participating facility from the AEDC value, divided by the AEDC value, and multiplying this value by 100 percent. AEDC BRDF data were obtained by a curve fit drawn through the August 20, 1974, scatter measurements. At the bottom of each table is the average deviation for all the mirrors measured at each facility. It is the sum of the average deviation for all of the mirrors, divided by the number of mirrors evaluated.

6.1 HONEYWELL RADIATION CENTER (HRC)

Results of the HRC, BRDF measurements for mirrors B-1, B-2, B-3, A-5, A-6, A-8, and A-9 are presented in Figs. 10 through 16. The HRC, BRDF data show approximately the same angular dependence as the AEDC BRDF data. Comparison of HRC and AEDC measurements on 14 mirrors are presented in Table 2. The highest HRC BRDF data was 67 percent above the AEDC data (mirror G-2). The lowest HRC BRDF data was -15 percent below the AEDC values (mirror A-7). There was no significant difference in the percent deviation between the HRC and AEDC data for the different quality mirrors. Average deviation between the HRC and AEDC data for all the mirrors was only 24 percent. Some data included in Figs. 13 through 16 and in Table 2 were very close to the minimum BRDF measurement capability of both the AEDC and HRC scatterometers. Detector noise and maximum laser power limit both systems to nominally 10^{-6} sr^{-1}.

The scatterometer used at HRC was just put into operation, and no data reduction method had been established. No comparison of data reduction technique is, therefore, presented.

6.2 ROCKWELL INTERNATIONAL (RI)

Only three mirrors (B-1, B-2, and A-5) were measured at RI. Results of the measurements are presented in Figs. 10, 11, and 13, and in Table 3. The highest RI BRDF data was 104 percent above the AEDC data (mirror B-2) and the lowest was 41 percent below the AEDC data (Table 3). This is almost a factor of two above and below AEDC measurements. Data presented for mirror A-5 (Fig. 13) are very close to the minimum measurable BRDF for the RI scatterometer (approximately 10^{-5} sr^{-1}). Large increases and decreases in the value of BRDF appear in the data for mirror B-2 as the angle from specular increased (Fig. 11). The lower values are very near the AEDC values. The RI data presented for mirrors B-1 (Fig. 10) and A-5 (Fig. 13) show approximately the same angular dependence as the AEDC data for these mirrors. Average deviation between the RI and AEDC BRDF data for the three mirrors was only 20 percent.

Mirror BRDF was calculated using the AEDC diffuser method. Mirror BRDF is normally calculated at RI by the incident power method presented in Section 5.1 of this report (Eq. (4)). Mirror BRDF calculated using this method and Eq. (4) would have been about 15 percent higher than that calculated using the AEDC diffuser method.

6.3 AEROSPACE CORPORATION

Aerospace BRDF data for six mirrors (B-1, B-2, B-3, A-5, A-8, and A-9) are presented in Figs. 10 through 13 and Figs. 15 and 16. Aerospace BRDF data shows approximately the same angular dependence as the AEDC BRDF data, with the exception of that for mirror A-9. BRDF for mirror A-9 appears to be independent of angle beyond 1.8 deg from specular. This characteristic is typical for mirrors that become contaminated with a large number of small particles. Attempts were made to clean mirror A-9 at Aerospace but this proved impractical without the use of a clean air facility.

Percent deviation between Aerospace and AEDC BRDF data for all the mirrors except A-9 are presented in Table 4. The highest Aerospace

BRDF data were 74 percent above the AEDC data, and the lowest Aerospace data were 39 percent below the AEDC data. There was no particular difference between the percentage deviation between the different quality of mirror tested. Average deviation between the Aerospace and AEDC BRDF data for all the mirrors (except A-9) was nominally 30 percent.

Mirror BRDF at Aerospace is calculated using the diffuse reflection method. Aerospace is currently using a KC1 diffuser, made by pressing KC1 powder into a cup-shaped container. The radiometer signal from the AEDC diffuser averaged about 30 percent higher than that from the KC1 diffuser; therefore, BRDF data based on the KC1 diffuser would be about 30 percent higher than the data presented.

Part of the 30-percent discrepancy was probably due to nonrepeatability of the radiometer signals as measured from the diffuse reflectors. Radiometer signals recorded when using the KC1 diffuser varied as much as 47 percent from one run to another. Not enough data was taken to get a good average radiometer signal from each diffuser because time was not available.

No large variations in total laser power were observed during times when there were significant changes in the scanning detector output (detector viewing diffuser). This indicates that the CO_2 laser may have been changing modes. The detector image was almost the same size as the laser beam (at the test mirror location) when the laser was operating in the TEM_{ooq} mode. If the laser changed to another operating mode, the beam diameter at the test mirror would increase. Detector output would then decrease because energy outside the detector image could not image onto the detector.

6.4 HUGHES AIRCRAFT

Results of Hughes BRDF measurements for mirrors B-1, B-2, A-5, A-6, and A-13 are presented in Figs. 10, 11, 13, 14, and 17, respectively. Hughes BRDF data have nominally the same angular dependence as the AEDC BRDF data. The BRDF value plotted at 6 deg for mirror A-13 appears to be high. This mirror had not been cleaned after being used for BRDF measurements at other facilities, and it is believed that its surface had been contaminated. Time was not available to clean and re-measure the BRDF of the mirror.

Percent deviation from the AEDC data for the above mirrors are presented in Table 5. The highest Hughes BRDF data were 54 percent above the AEDC data (mirror A-13). Only the BRDF values at 3 and 4 deg were used to calculate the average percent deviation. Values of BRDF data at angles below 3 deg were not used because there are no AEDC measurements below this angle with which to make a comparison. The 6-deg Hughes BRDF measurement was not used because it was believed a measurement of mirror contamination rather than that of the mirror surface. It should be noted that the Hughes BRDF data are generally below the AEDC BRDF data. Average deviation between the Hughes and AEDC data for all the mirrors was nominally -22 percent.

Presented in Fig. 17 are measurements made by swinging the radiometer arm 180 deg from its normal position. These data represent the lowest BRDF that could be measured at each angle when testing a flat mirror (for this particular scatterometer configuration). System and mirror BRDF for mirror A-13 (Fig. 17) were identical for the 0.5- and 1.0-deg angle measurements. (The 0.5-deg BRDF, not shown in Fig. 17, was nominally 0.13 sr^{-1}.) This demonstrates the effectiveness of this system checkout technique.

Mirror BRDF at Hughes Aircraft is calculated using the diffuse reflector method presented in Section 5.2 (Eq. (8)). Two different Hughes diffusers were compared with the AEDC diffuser. One was similar to the AEDC diffuser, except that it was not gold coated; the other was F150 sintered bronze. Radiometer signal from all three diffusers varied considerably in a random manner as the radiometer was rotated about the surface of the diffuser. This was a result of the radiometer small collection solid angle and the random speckle characteristic of the diffusers. The radiometer signal used to calculate BRDF was an average value determined by recording the radiometer output voltage on a strip-chart recorder as the radiometer arm was rotated about the sample surface. Radiometer signal from the Hughes F150 bronze diffuser was approximately 35 percent below that from the AEDC diffuser. BRDF data, based on this diffuser, would be about 30 percent higher than that based on the AEDC diffuser. Data from the painted Hughes diffuser was in agreement with the AEDC diffuser. Measurements made with the two Hughes diffusers had been in agreement prior to the Round-Robin measurements. It should be noted that almost all of the Hughes BRDF measurements were between 20 and 60 percent below the AEDC measurements, indicating a problem with measurement of radiometer signal while viewing the AEDC diffuser. Time did not permit a more thorough evaluation of the diffuse reflectors.

6.5 NAVAL WEAPONS CENTER (NWC) OPTICAL EVALUATION FACILITY

The NWC Optical Evaluation Facility was recently modified to permit BRDF measurements. Of particular interest for the Round-Robin program were BRDF measurements at 10.6 μm. The first measurements were made with no mirror and the detector arm swung 180 deg from its normal position. A plot of minimum measurable BRDF versus angle is presented in Fig. 18. Stray radiation was too high to make BRDF measurements on any Round-Robin mirrors. Scatter measurements were made for mirror B-1 to illustrate the effectiveness of the stray radiation test. General agreement exists between the stray radiation test and the BRDF data for this mirror (Fig. 18). The peaks occurring at 2.1, 3.1, 5.7, and 6.5 deg were probably caused by diffraction of the beam as it reflected from the mirror surface, back through the aperture in front of the mirror. The horizontal line in Fig. 18 is the minimum BRDF that can be measured from 7.4 to 14 deg. This value was measured by making a test run in the normal scatterometer configuration, without a test mirror in place. Detector signal for these angles resulted from laser energy reflected from the aperture placed just in front of the mirror.

Stray radiation tests were next conducted using a 0.6471-μm radiation source. This laser has a smaller beam diameter than the CO_2 laser. Results of the stray radiation test and BRDF measurements for mirrors B-1 and B-2 are presented in Figs. 19 and 20. Stray radiation within the system was negligible for angles past 1.8 deg. Agreement between the NWC and AEDC measurements was exceptionally good at this wavelength. Note that the BRDF at 0.9 deg for mirror B-1 (Fig. 19) and at 1 deg for mirror B-2 (Fig. 20) are very close to the system lower limit for these angles.

The diffuse reflector technique (AEDC diffuser) was used to obtain the NWC BRDF data. At the time of the Round-Robin measurements, no technique had been used at NWC to calculate mirror BRDF. The facility was used to compare scatter from different optical elements; thus, no data reduction was required. However, a form of the incident power method was used to make a comparison with the diffuser method. Incident power was measured with the scanning detector swung 180 deg from its normal measurement position, without a test mirror in place. The laser beam was nominally 1-mm diameter at the $1/e^2$ power points; therefore, not all of the laser energy was collected by the scanning detector (detector size was 2 by 0.5 mm) when peak detector signal was obtained. An equivalent detector voltage for the incident power measurement was calculated by adding the peak detector signal to twice the

detector signal measured at 0.15 and 0.45 deg away from the peak signal position. This equivalent detector signal was used for V_i in Eq. (1), Section 5.1 of this report. BRDF values obtained by this method and the diffuse reflector method agreed to within 15 percent (Ref. 4).

6.6 HONEYWELL SYSTEMS AND RESEARCH CENTER (HS&RC)

Results of HS&RC BRDF measurements for mirrors B-1, B-2, A-5, and A-6 are presented in Figs. 10, 11, 13, and 14, respectively. HS&RC BRDF data have approximately the same angular dependence as the AEDC data, with the exception of the BRDF data for mirror A-6. The first two BRDF measurements at 2 and 3 deg are very close to the AEDC measurements for those angles. However, a step change occurred at 4 deg and continued for the 5- and 6-deg measurements. It should be noted that the HS&RC lower limit for BRDF measurements was nominally 10^{-5} sr^{-1}, and that, at the 4-deg measurement, the signal-to-noise ratio was only three. At 6 deg, the radiometer signal-to-noise ratio was only one.

Percent deviation of the HS&RC BRDF data from the AEDC data for mirrors B-1, B-2, A-5, and A-6 are presented in Table 7. The highest HS&RC BRDF data were 118 percent above the AEDC data, and the lowest HS&RC data were -53 percent below the AEDC data. This is about a factor of two above and below the AEDC data. Average deviation between the HS&RC and AEDC data for all four mirrors was nominally 45 percent (HS&RC data above AEDC data).

Scatter data (HS&RC) at one degree from specular were much higher than AEDC data and were not included in this report. The problem was of angular definition. Zero angle was defined as the angle when the specular beam was in the center of the collecting mirror aperture. When the radiometer was rotated to make the one degree measurement, the collecting angle was from 0.13 to 1.87 deg. At 0.13 deg, the edge of the collecting mirror aperture was less than 1 mm from the center of the specular beam, (assuming the specular beam was perfectly aligned in the center of the collecting mirror aperture). The specular beam was only visibly aligned to the approximate center of the collecting mirror using the He-Ne laser, without the aid of any alignment fixtures. Therefore, it is very probable that the detector was receiving energy directly from the specular beam at the one-degree angular measurements.

The diffuse reflector method is used at HS&RC to calculate mirror BRDF. The HS&RC diffuse reflector was 240 grit sandpaper, with an evaporated gold overcoating. Radiometer signal obtained when using this diffuser was the same as when the AEDC diffuser was used; therefore, there was no difference between the AEDC and HS&RC data reduction techniques.

6.7 PERKIN-ELMER (P-E)

Results of Perkin-Elmer BRDF measurements for mirrors B-1 and B-2 are presented in Figs. 10 and 11, respectively. Perkin-Elmer data show the same angular dependence as the AEDC data. Percent deviation of the Perkin-Elmer data from the AEDC data for the above two mirrors is presented in Table 8. The percent deviation for mirror B-1 was -51 percent; whereas, percent deviation for mirror B-2 was +35 percent. Average deviation between the Perkin-Elmer and AEDC data for both mirrors was only -8 percent.

Scatter data could not be taken using the "super polished" aluminum mirrors because of the stray radiation in the Perkin-Elmer scatterometer. Stray radiation was measured with the detector arm swung 180 deg from its normal position, with the detector viewing the converging mirror. Results of this measurement are presented in Fig. 21. Data recorded during the Round-Robin program were slightly higher than stray radiation data reported by Perkin-Elmer in late 1972. This is probably because the converging mirror has become dirtier in the interim. Results of BRDF measurements for mirror A-13 are also presented in Fig. 21. The high values of BRDF for this mirror results from stray radiation within the scatterometer. The data for mirror A-13 are lower than the system data because the test mirror reduces the detector field of view of the converging mirror.

Another problem associated with the Perkin-Elmer facility is the laboratory environment. The scatterometer is located in a fairly dirty room, and the converging mirror and test mirror are exposed to the room environment. Even if the stray radiation within the scatterometer were drastically reduced, the scatterometer could still not measure mirrors with a BRDF below nominally 5×10^{-6}, because the test mirror becomes contaminated before the BRDF measurements could be made.

Mirror BRDF presented in this report was calculated using the diffuser method of Section 5.2. Mirror BRDF is normally calculated at

Perkin-Elmer by the incident power method (Section 5.1, Eq. (1)). Incident power is measured with a power meter, and scattered power is measured with the scanning detector. No calibration is performed at Perkin-Elmer; the calibrations supplied by the vendor of each instrument are assumed correct. Collection solid angle is the detector area divided by its distance from the test mirror. Mirror BRDF would have been nominally 23 percent below that calculated using the AEDC diffuser method.

7.0 CONCLUDING REMARKS

Mirror scatter measurements made at the seven participating facilities and at AEDC were in general agreement. Data obtained on individual mirrors varied from nominally plus or minus a multiple of two from the AEDC data. This was not considered unreasonable, because mirror BRDF generally varies by at least a factor of three at different locations on a mirror surface. The agreement between measurements was considerably better when the average deviation from all mirrors measured at each facility was considered. Average deviation based on all mirror measurements at each facility varied from -22 to +45 percent. This is considered exceptional agreement for BRDF measurements, and much better than the orders of magnitude variation of measurements made in the past. It should be pointed out that the scatterometers used for the Round-Robin measurements were not in the same configuration as in the past. Most of the systems had undergone several modifications. The data presented in this report represent the state of scatterometer art as of this date and, because scatterometers appear to be in a continual state of refinement, may not be applicable in the future. Cooperation between facilities must be maintained in order to further the state of the art of scatterometer measurements.

REFERENCES

1. Young, R. P. "Degradation of Low Scatter Mirrors by Particle Contamination." AEDC-TR-74-109 (AD923579L), January 1975.

2. Bennett, H. E. and others. "High Energy Laser Mirrors and Windows." Semi-Annual Report No. 3, Michelson Laboratory, Naval Weapons Center, September 1973.

3. Bennett, H. E. and others. "High Energy Laser Mirrors and Windows." Semi-Annual Report No. 4, Michelson Laboratory, Naval Weapons Center, March 1974.

4. Bennett, H. E. and others. "High Energy Laser Mirrors and Windows." Semi-Annual Report No. 5, Michelson Laboratory, Naval Weapons Center, October 1974.

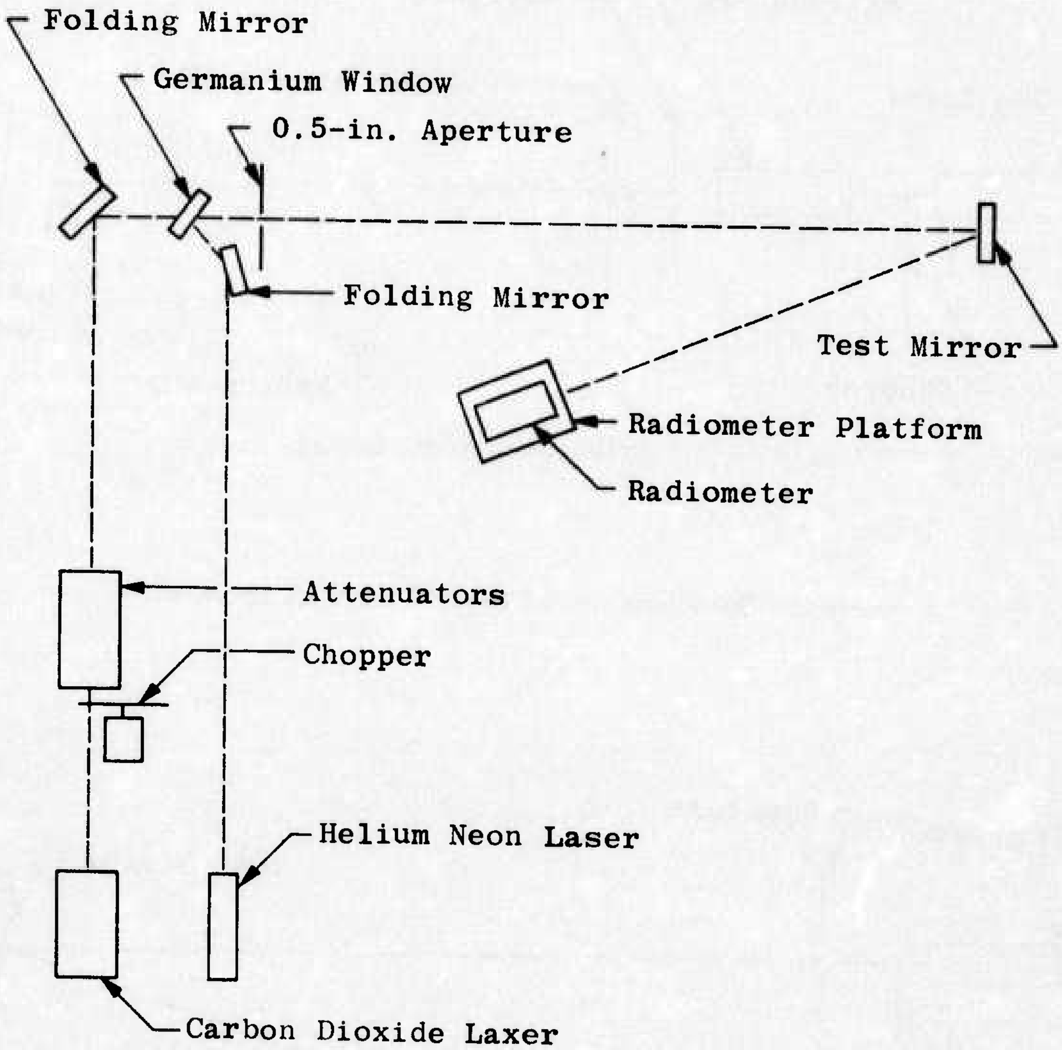


Figure 1. Block diagram of AEDC 10.6-μm scatterometer.

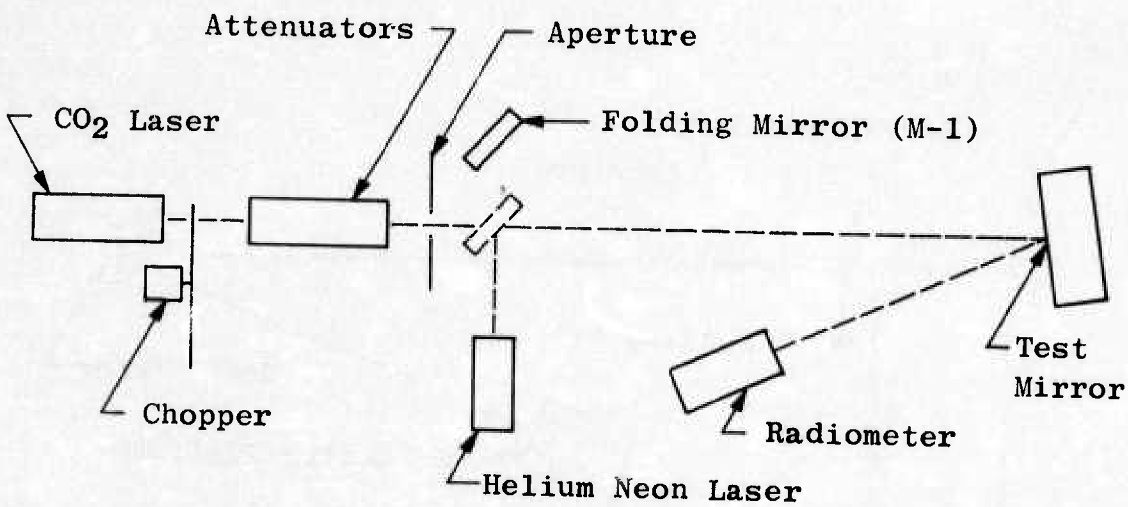


Figure 2. Block diagram of HRC 10.6-μm scatterometer.

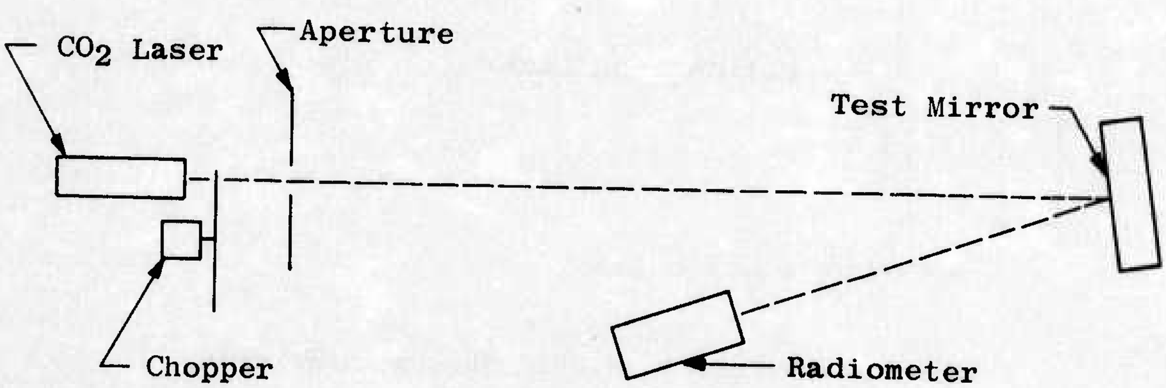


Figure 3. Block diagram of RI 10.6-μm scatterometer.

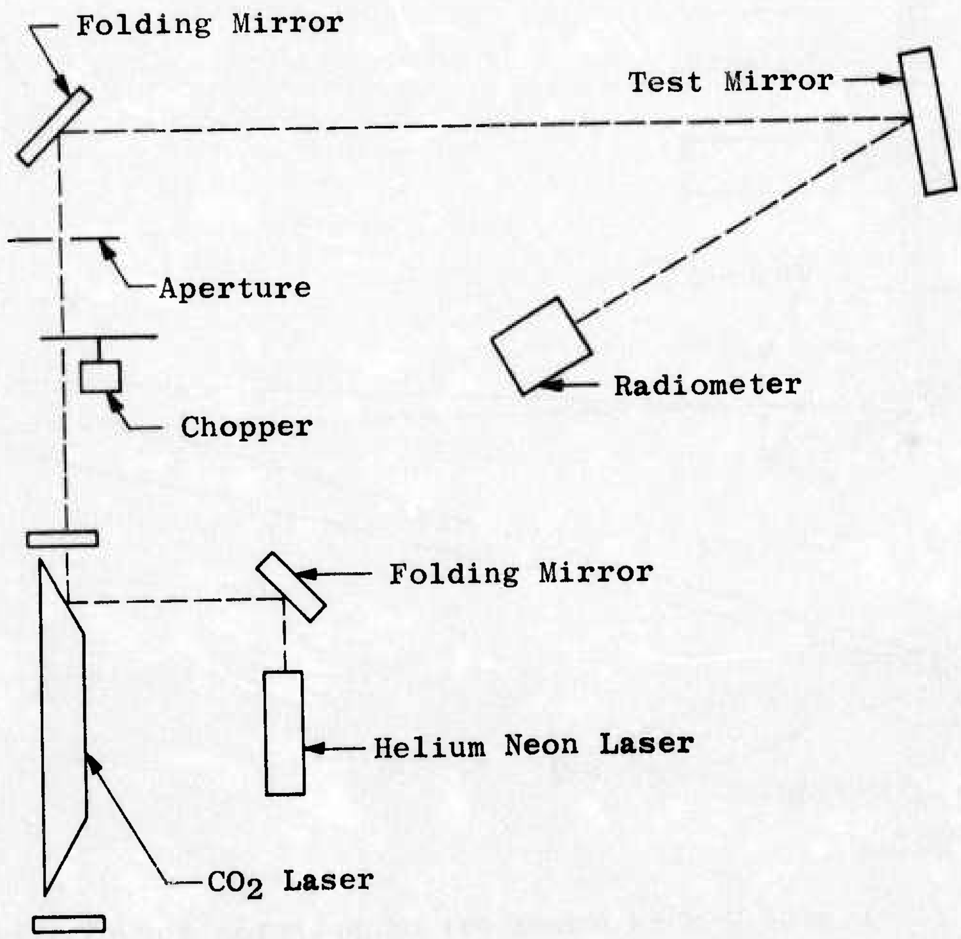
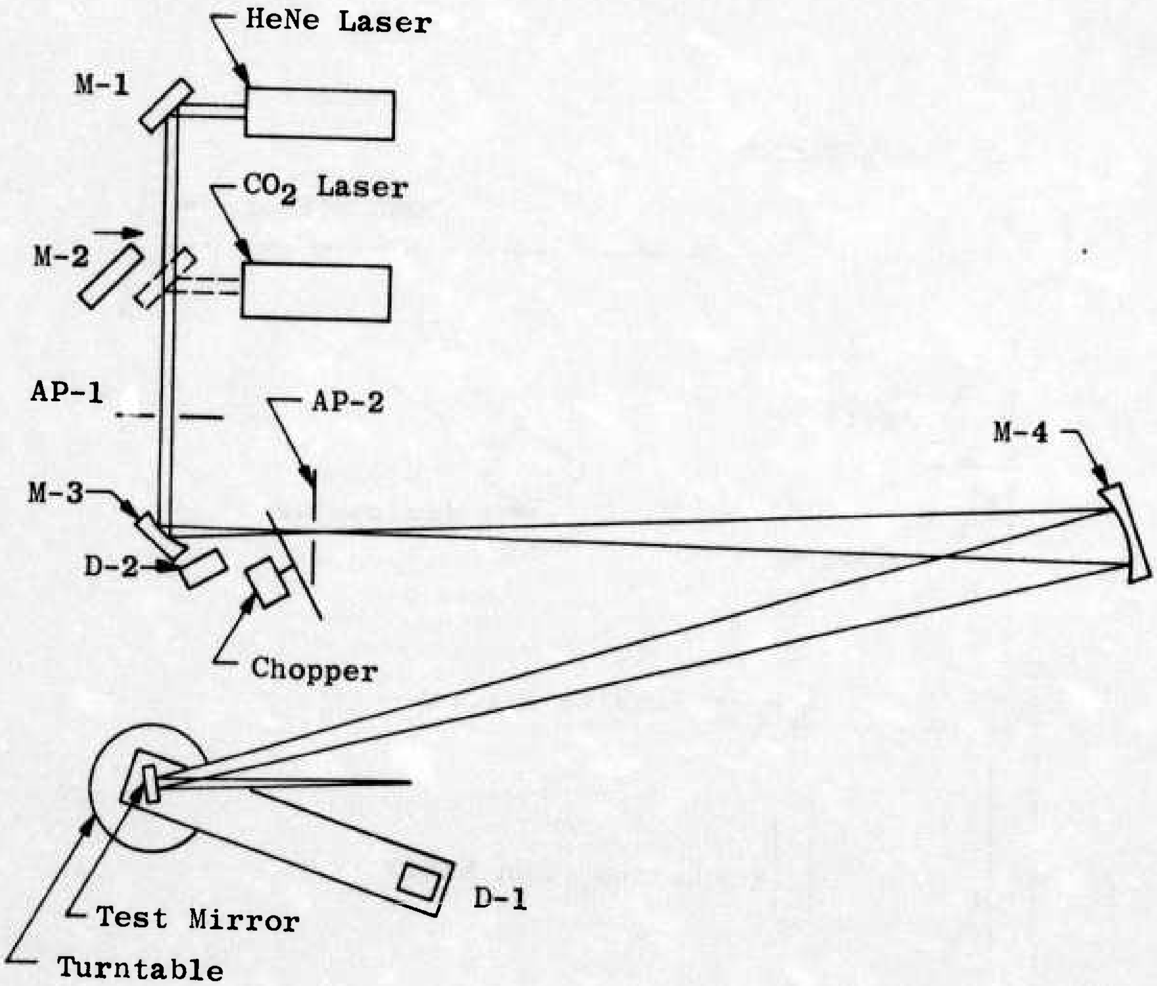
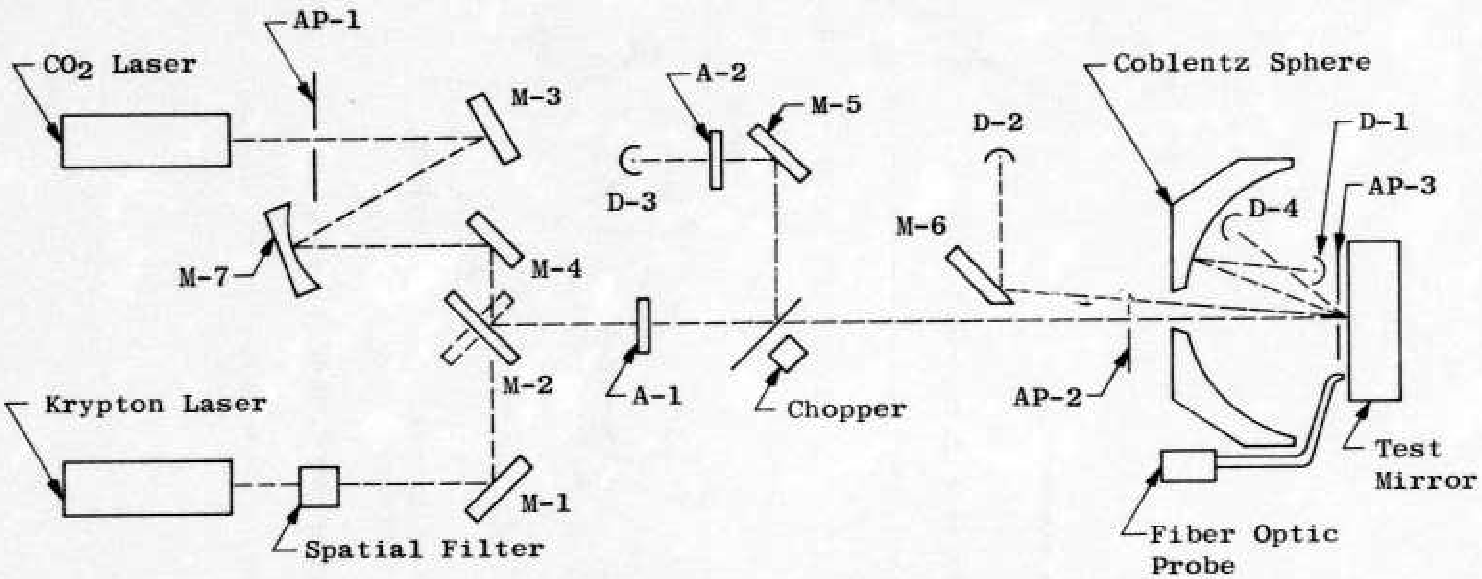


Figure 4. Block diagram of Aerospace 10.6-μm scatterometer.



Note:
1. Mirror M-2 is moved out of position for alignment.
2. Mirror M-3 is a toroidal focusing mirror.
3. Mirror M-4 converges the beam to the test sample.
4. Detector D-1 is used for BRDF measurements.
5. Detector D-2 is used to monitor laser energy.

Figure 5. Block diagram of Hughes aircraft 10.6-μm scatterometer.



Note:
1. Mirrors M-1, M-3, M-4, and M-6 are folding mirrors.
2. Mirror M-2 selects which laser is illuminating the test mirror.
3. Mirror M-7 is an 81-cm focal length converging mirror.
4. A-1 and A-2 are attenuators.
5. AP-1, AP-2, and AP-3 are apertures.
6. Detector D-1 is used to measure total scattered energy.
7. Detector D-2 is used to measure reflected energy from test mirrors.
8. Detector D-3 is used to monitor laser energy.
9. Detector D-4 is used to measure scattered energy for BRDF measurements.

Figure 6. Block diagram of NWC Optical Evaluation Facility.

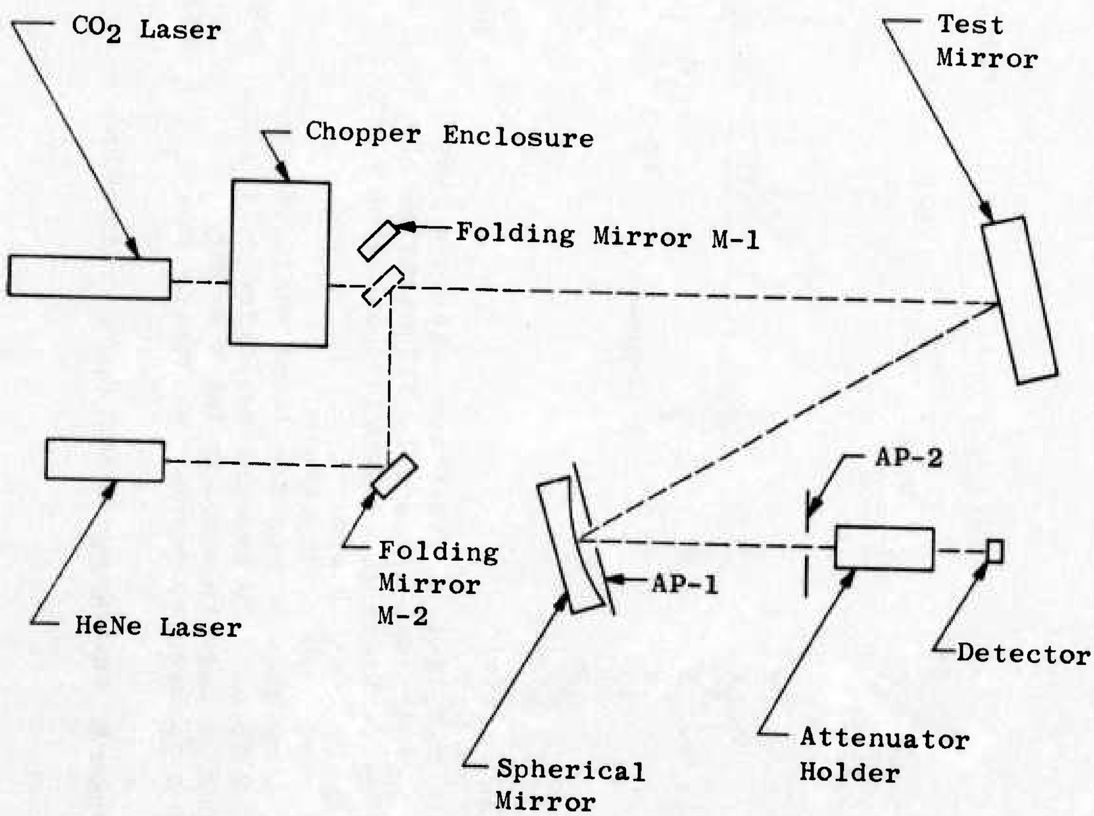
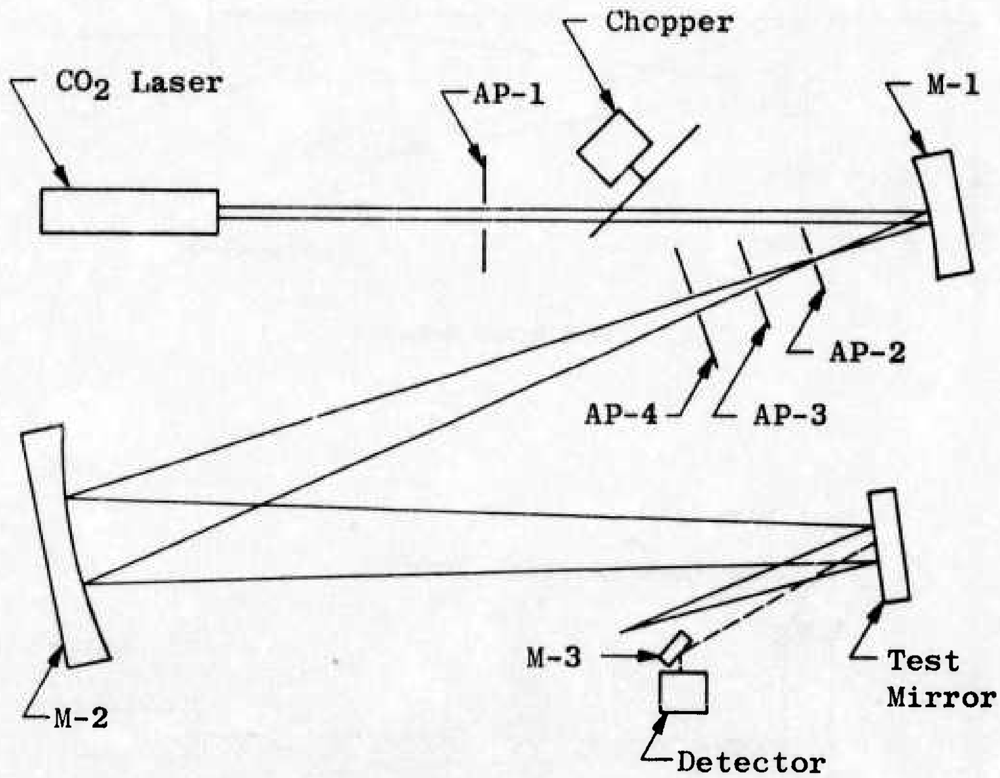
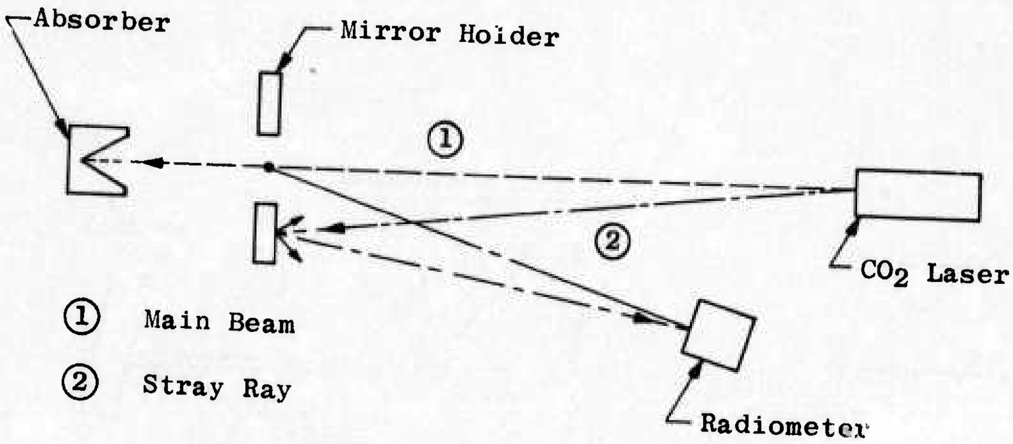


Figure 7. Block diagram of HS&RC 10.6-μm scatterometer.

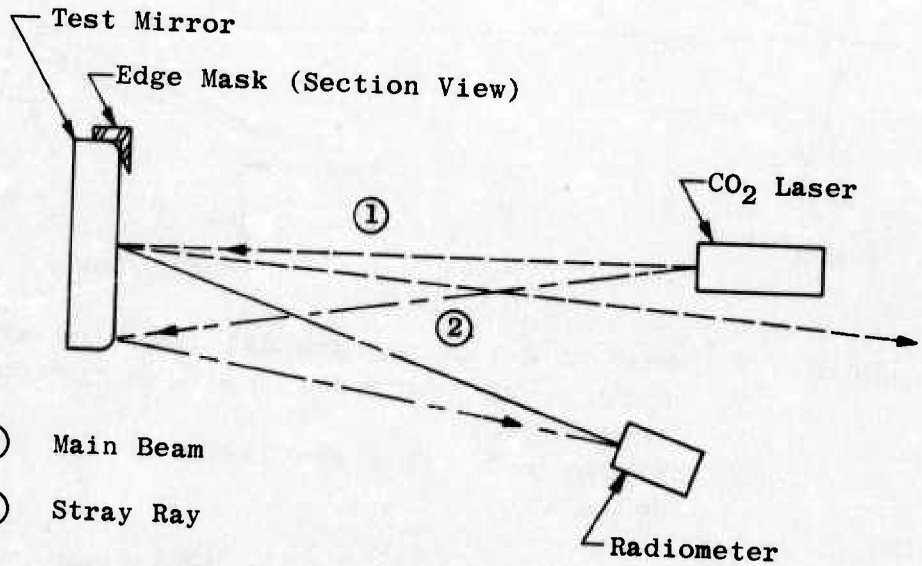


Note: 1. Mirror M-1 is a toroidal focusing mirror.
2. Mirror M-2 converges the beam toward the test mirror.
3. Mirror M-3 folds scattered energy onto the detector.

Figure 8. Block diagram of Perkin-Elmer 10.6-μm scatterometer.

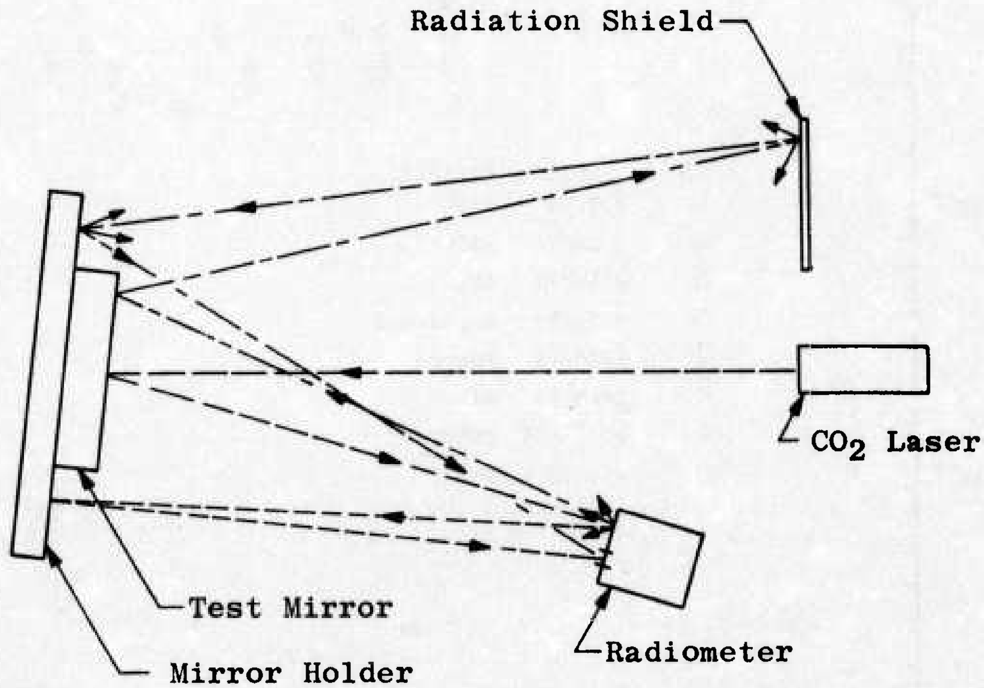


a. Holding fixture reflection



b. Mirror edge reflection

Figure 9. Sources of stray radiation in a typical scatterometer.



c. Specular beam reflection from radiometer holder
Figure 9. Concluded.

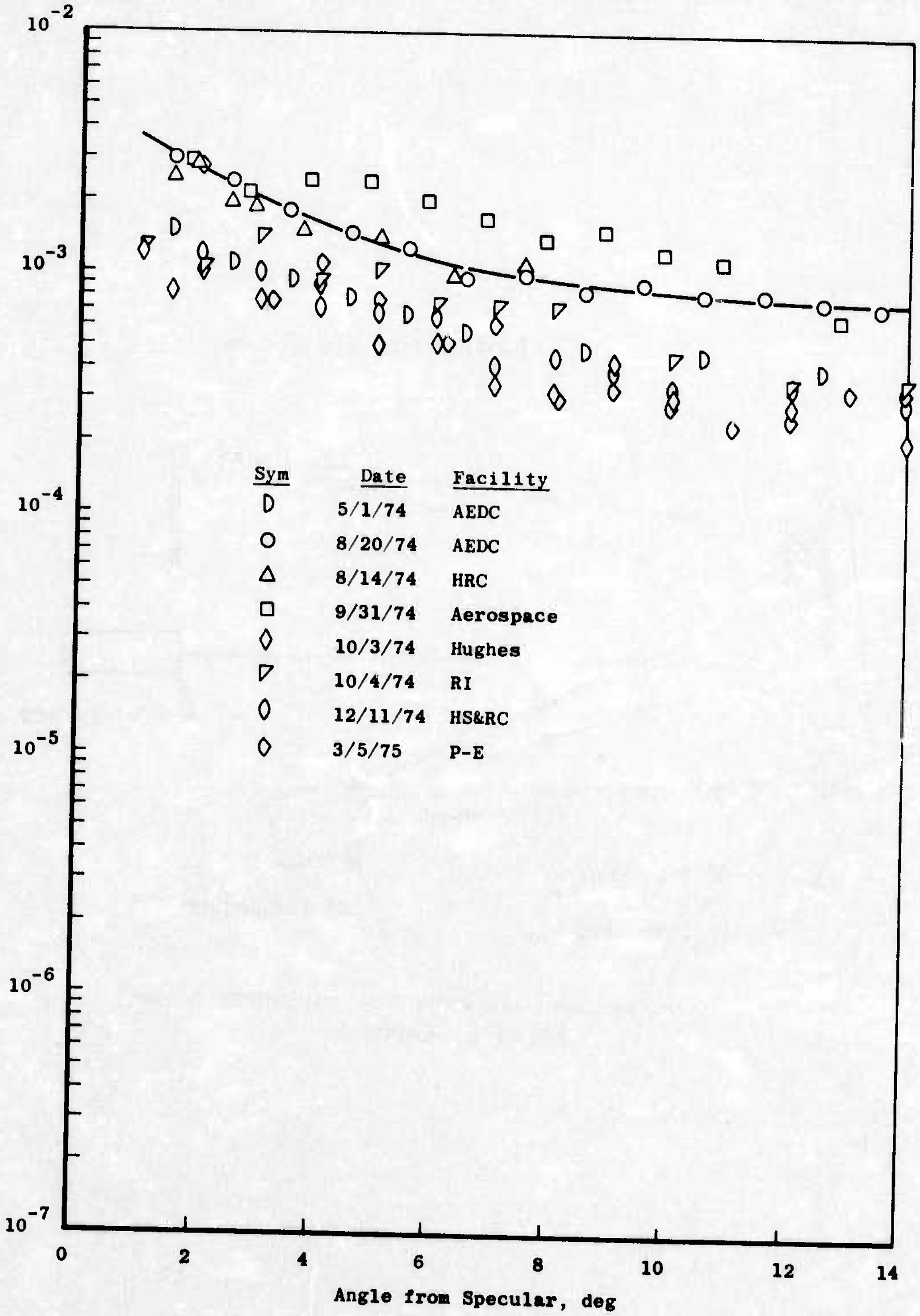


Figure 10. BRDF of mirror SN B-1 (10.6 μm).

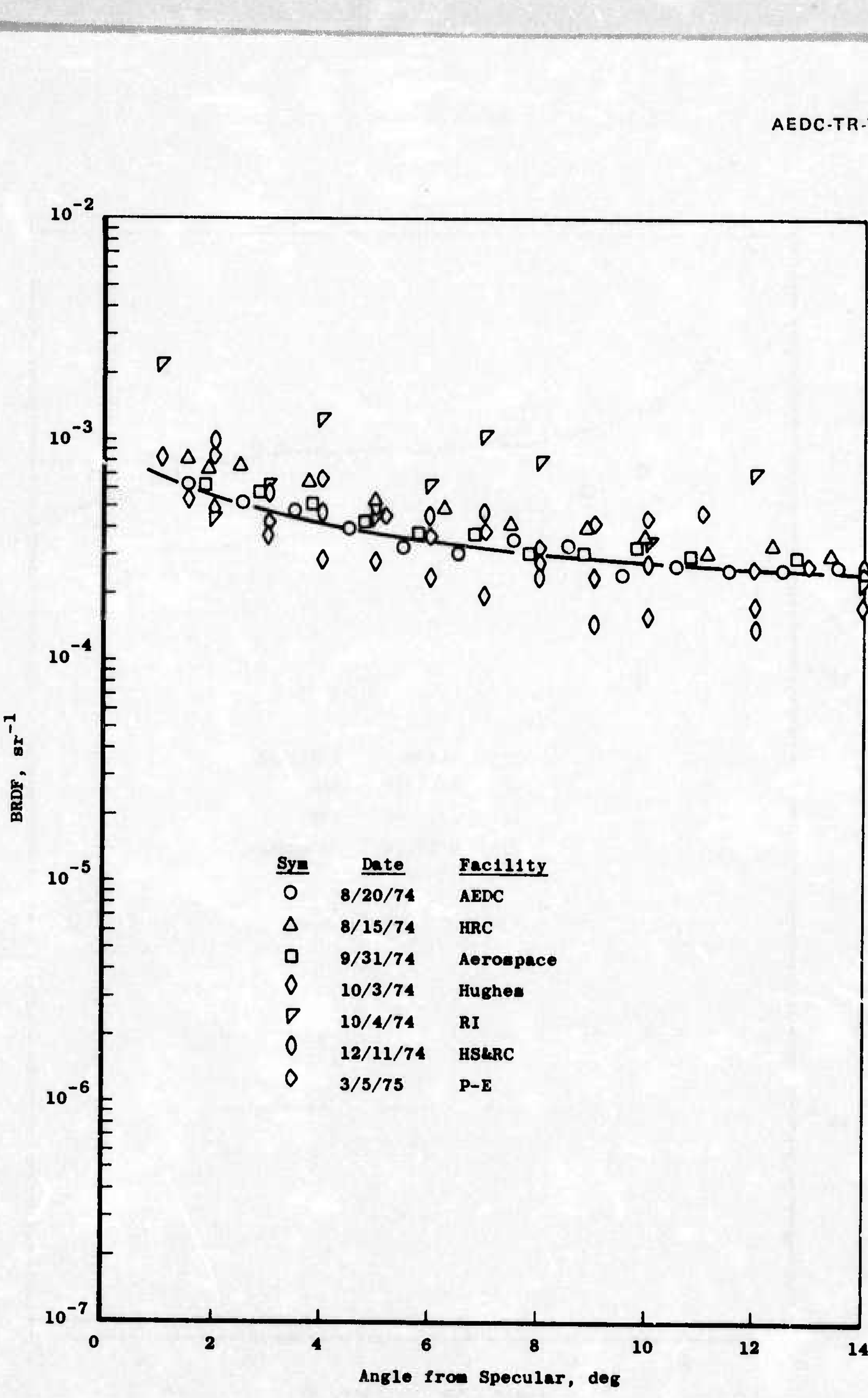


Figure 11. BRDF of mirror SN B-2 (10.6 μm).

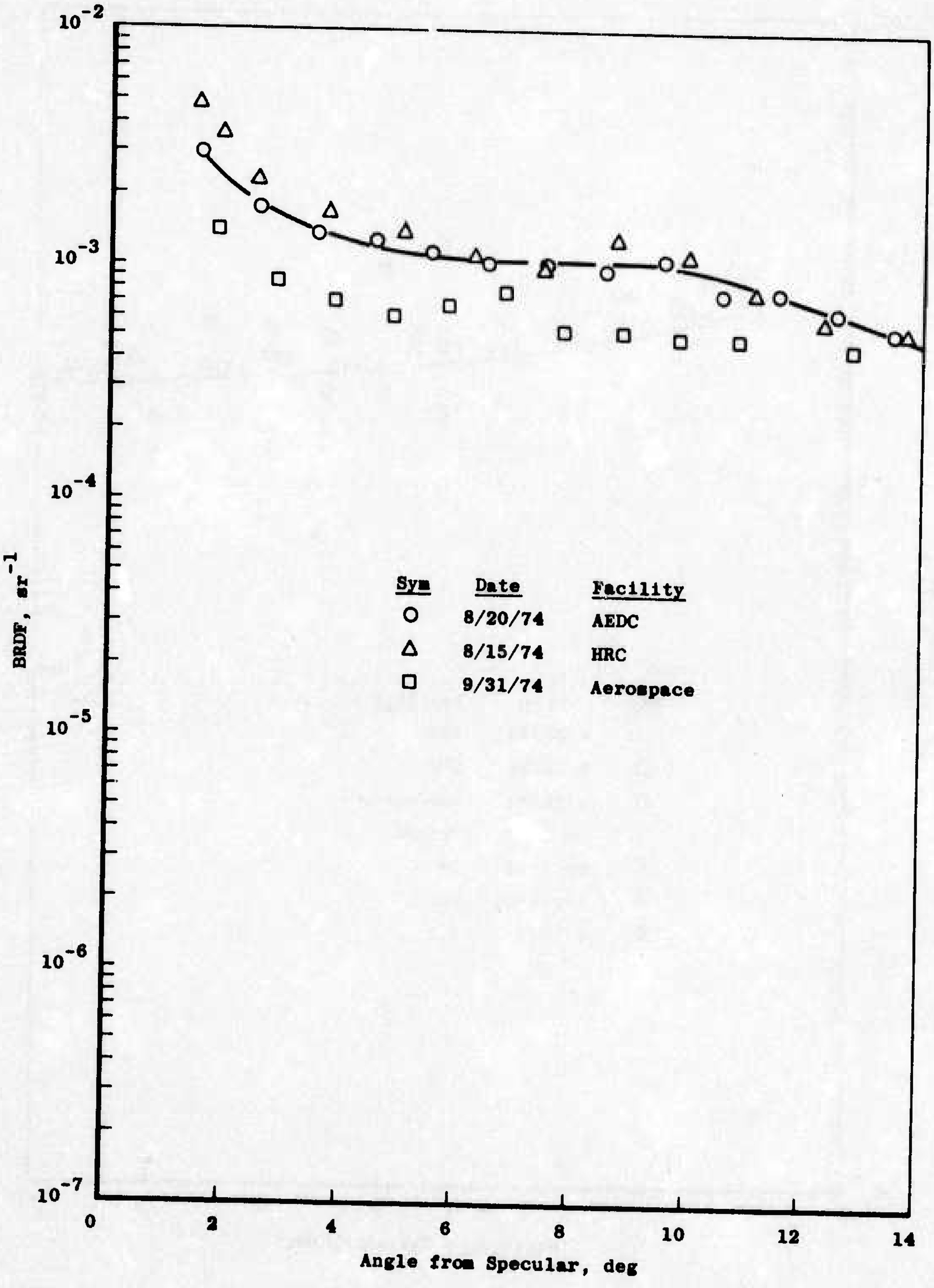


Figure 12. BRDF of mirror SN B-3 (10.6 μm).

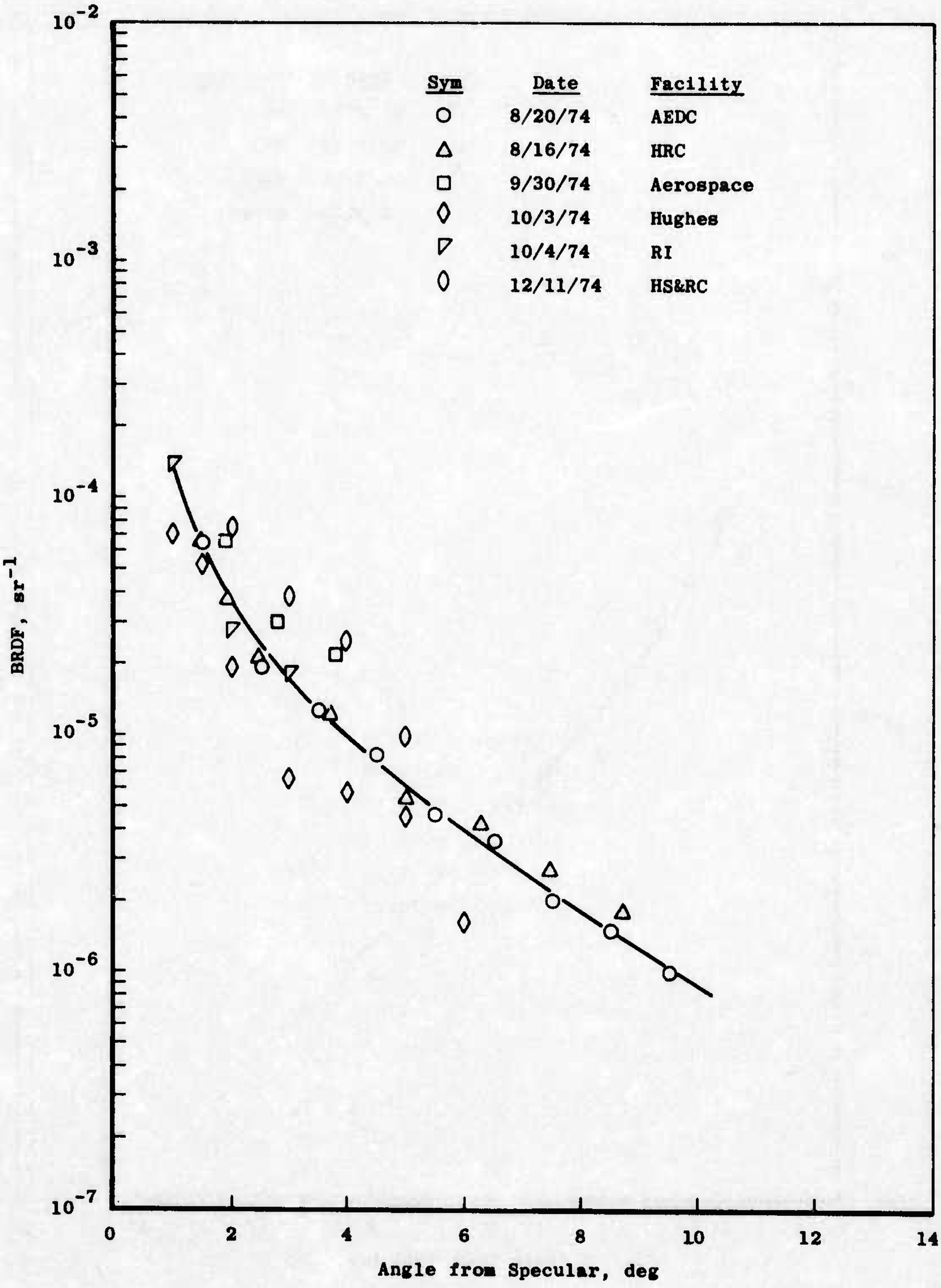


Figure 13. BRDF of mirror SN A-5 (10.6 μm).

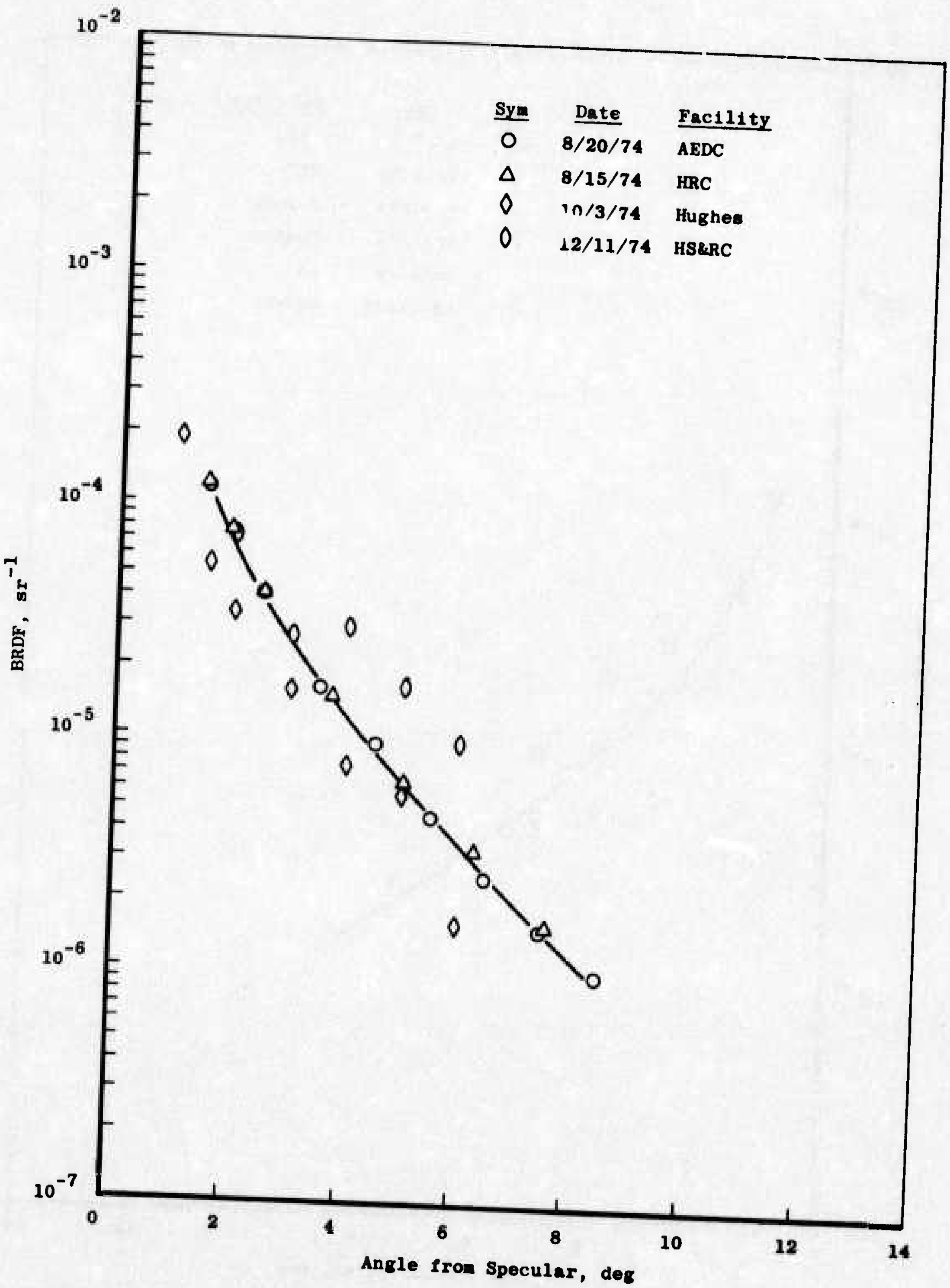


Figure 14. BRDF of mirror SN A-6 (10.6 μm).

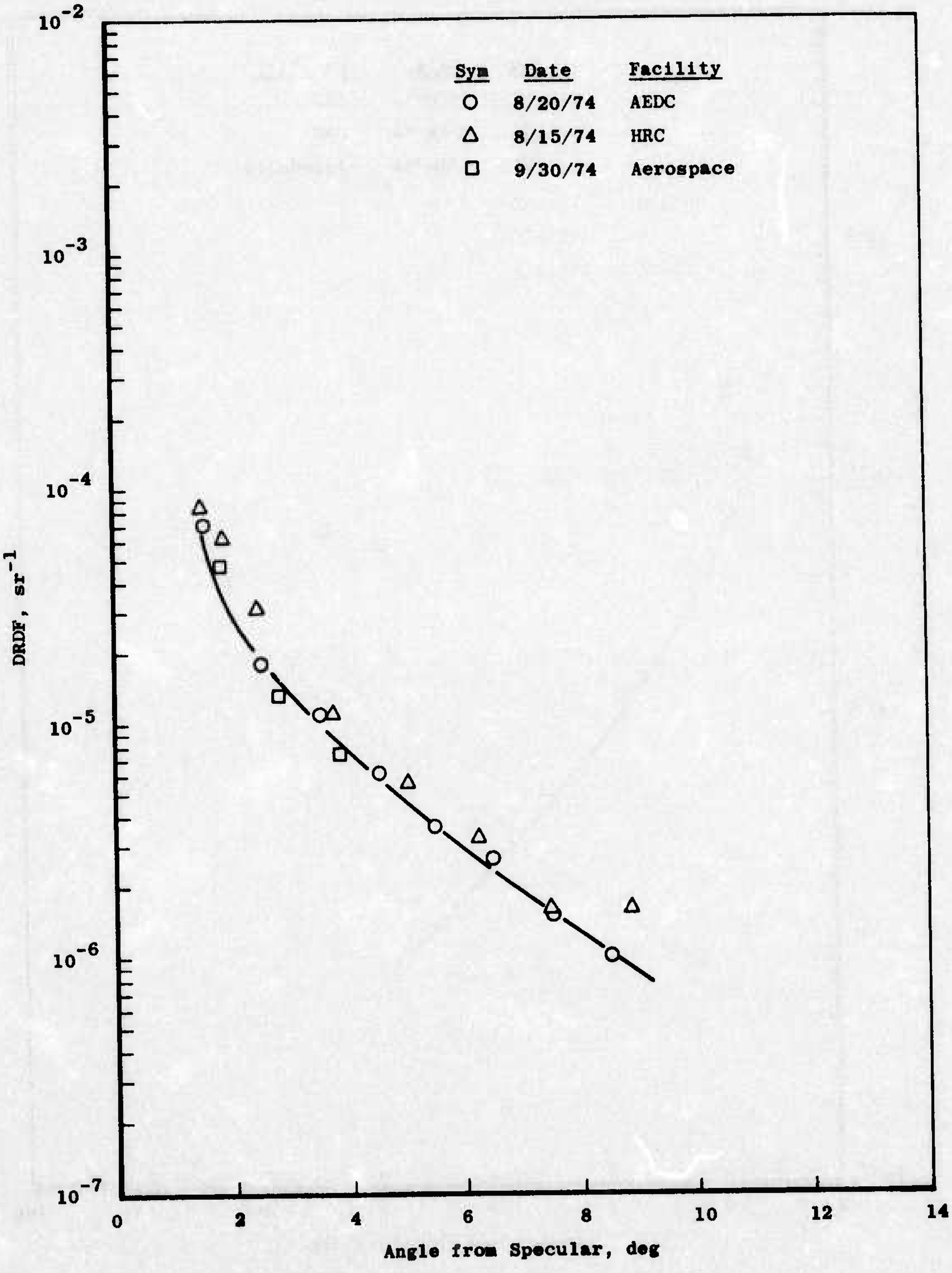


Figure 15. BRDF of mirror SN A-8 (10.6 μm).

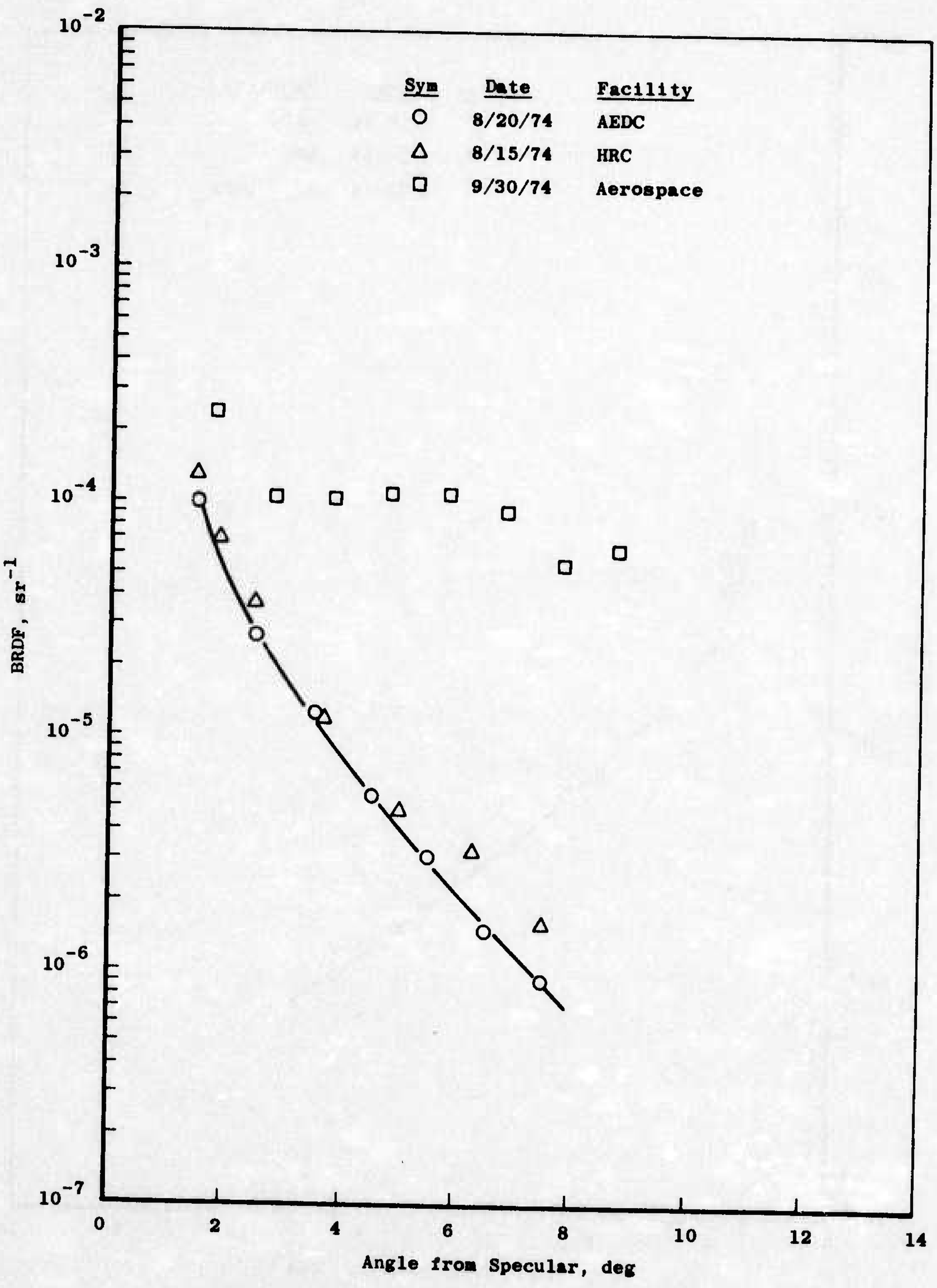


Figure 16. BRDF of mirror SN A-9 (10.6 μm).

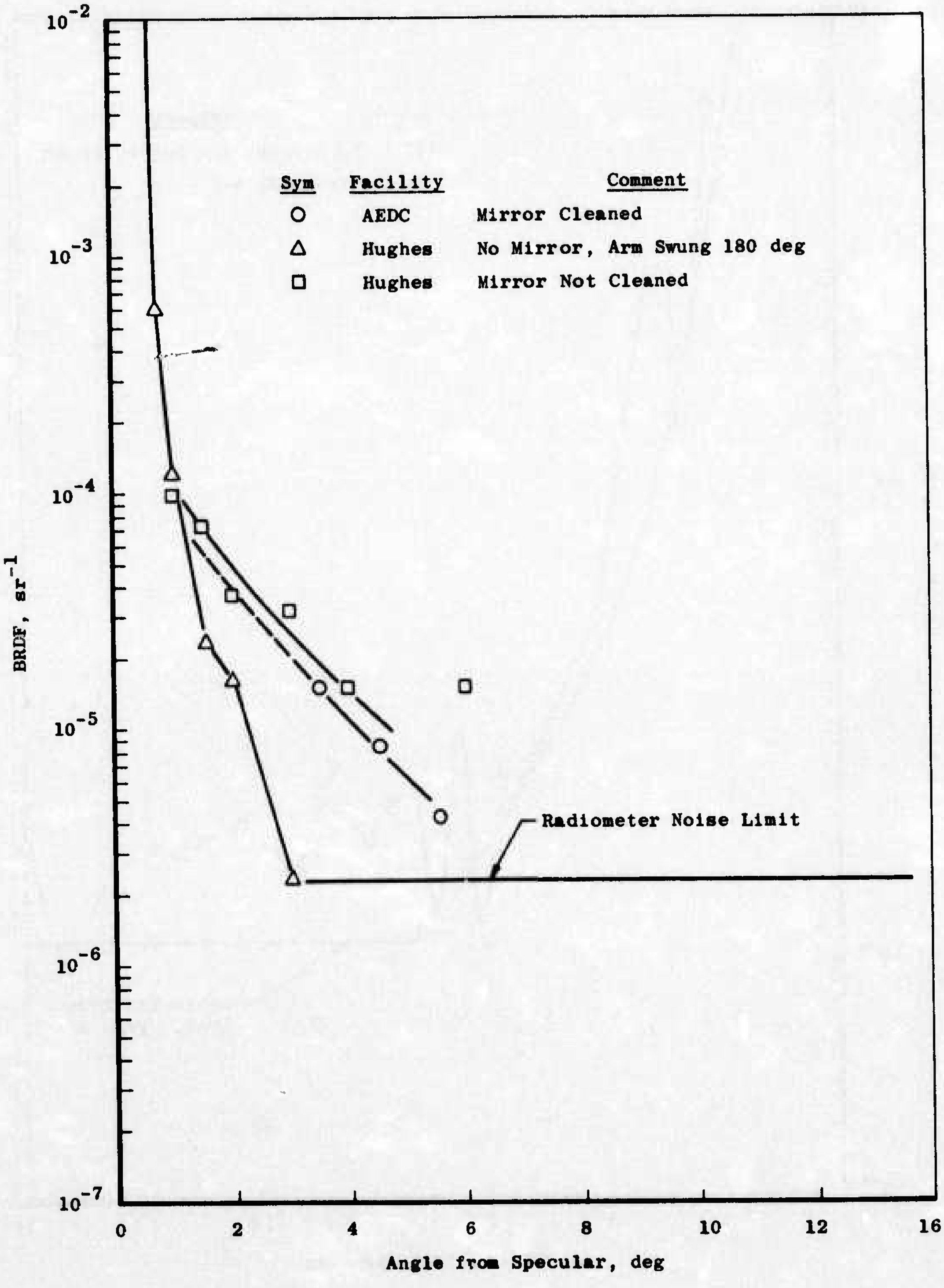


Figure 17. BRDF of mirror SN A-13 (10.6 μm).

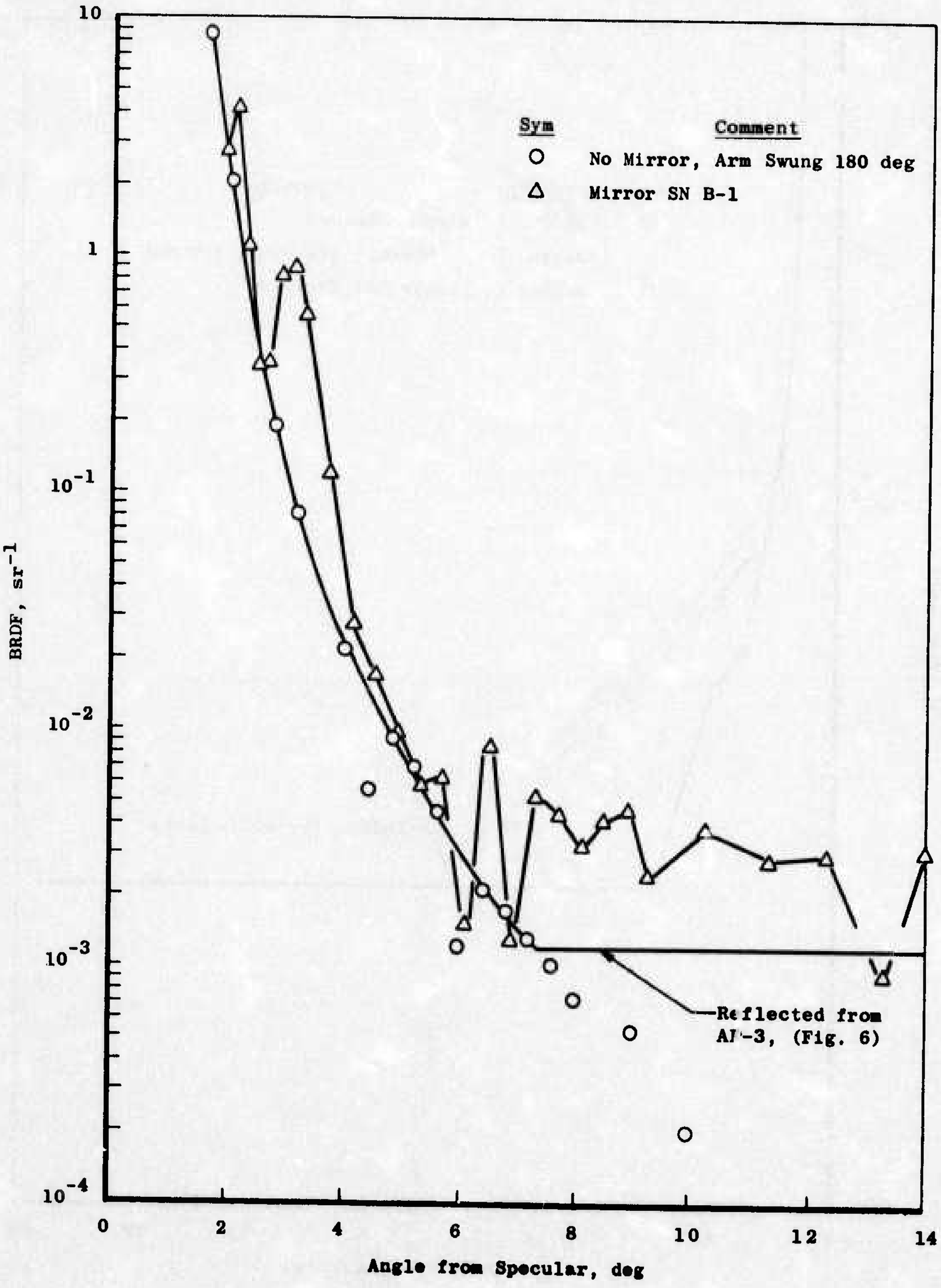


Figure 18. NWC 10.6-μm background radiation.

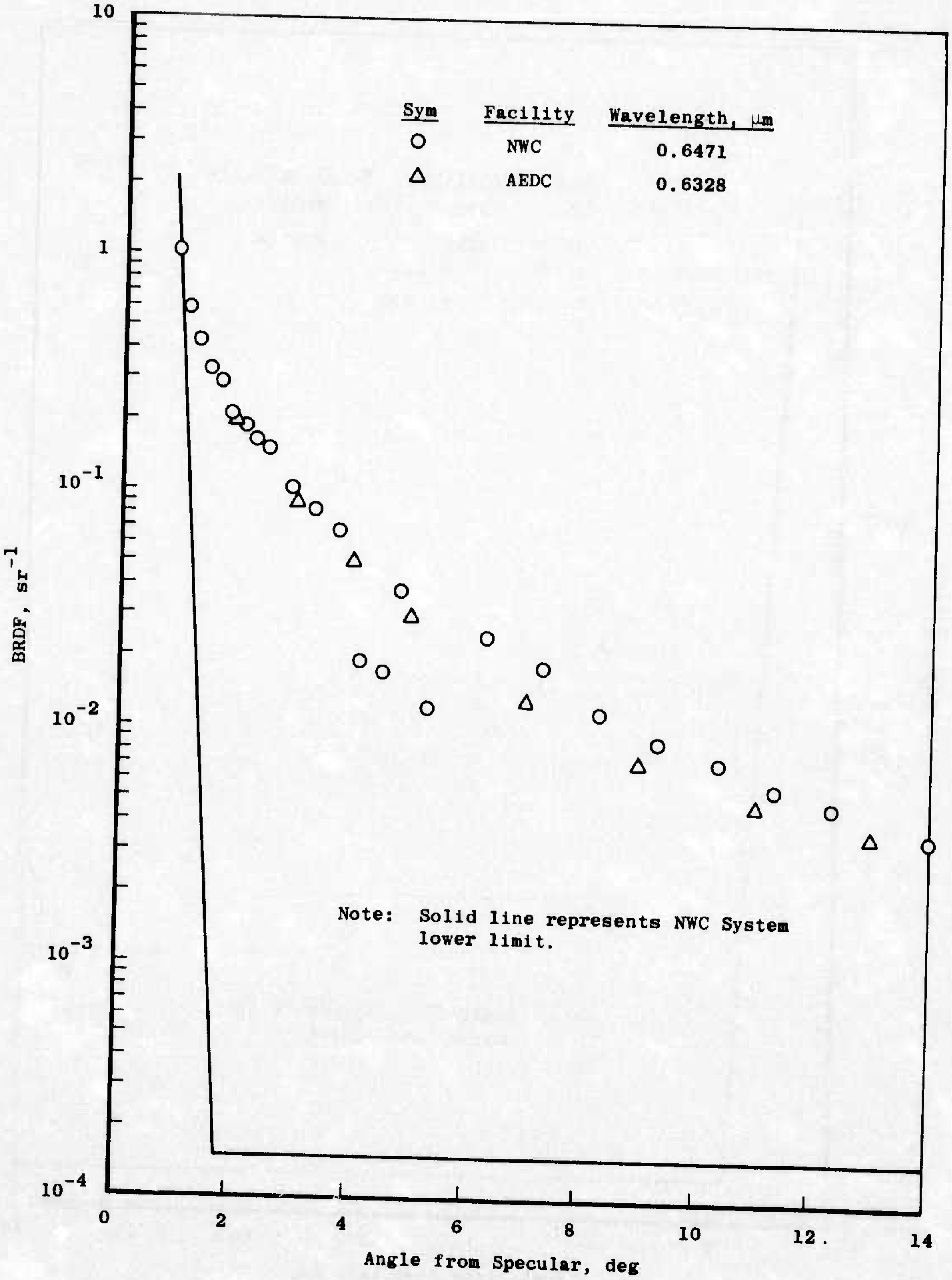


Figure 19. BRDF of mirror SN B-1 (visible).

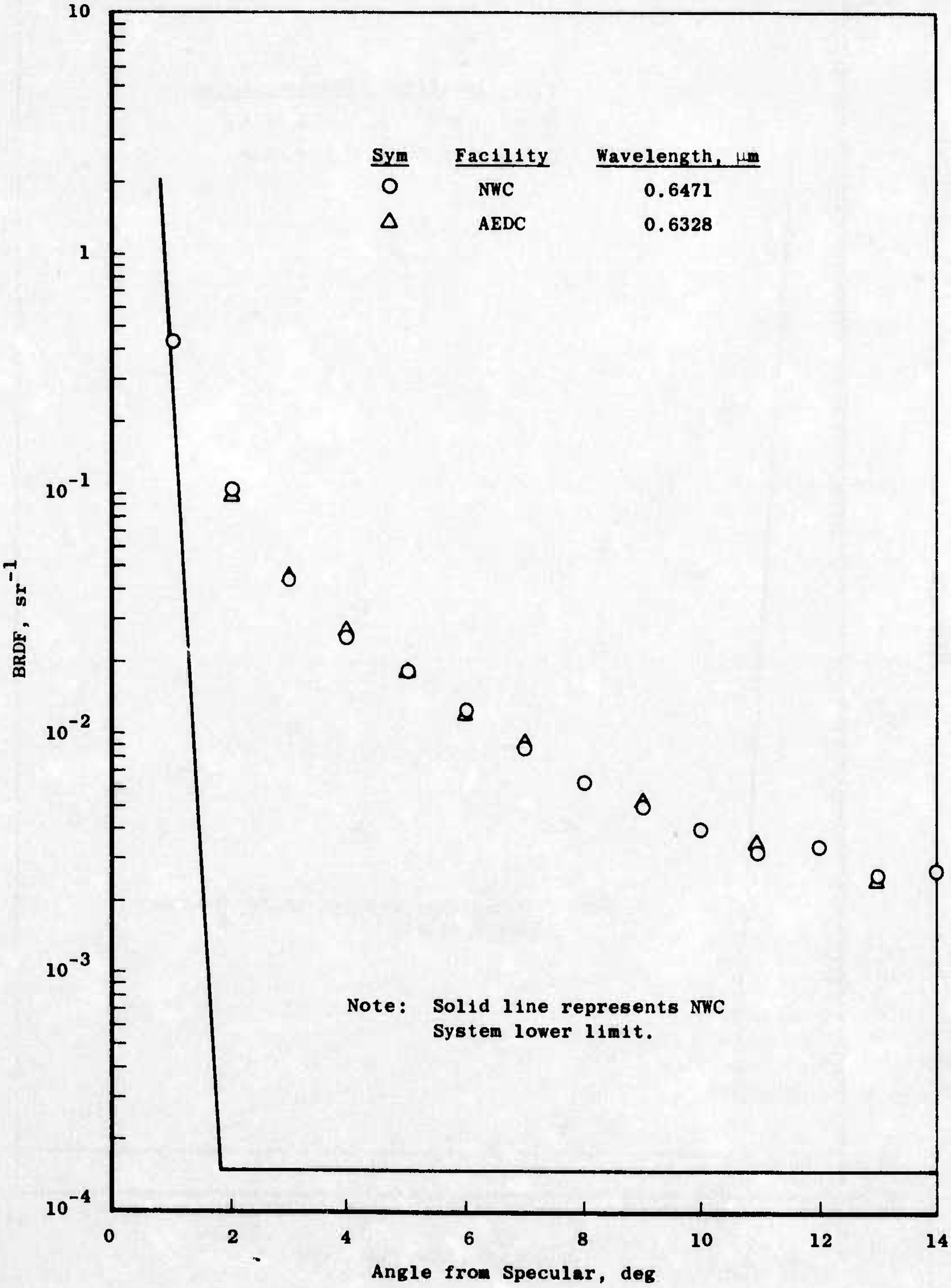


Figure 20. BRDF of mirror SN B-2 (visible).

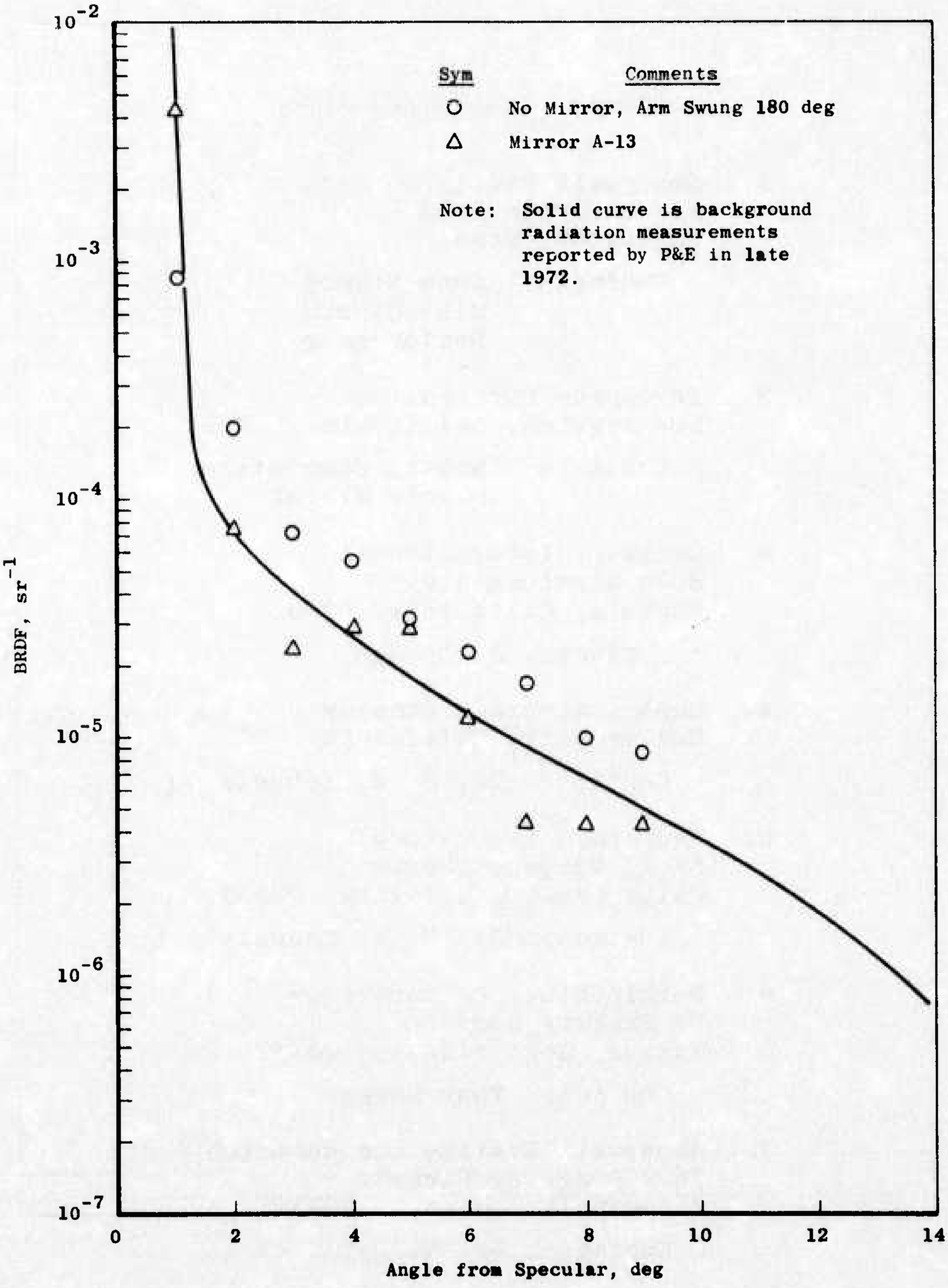


Figure 21. Perkin-Elmer 10.6-μm background radiation.

Table 1. Participating Facilities

1. Honeywell Radiation Center
   No. 2 Forbes Road
   Lexington, Mass.

   Contacts: John Nizney
   Mike Circio
   Dexter Wang

2. Aerospace Corporation
   Los Angeles, California 90009

   Contacts: Robert Champetier
   Harold Miller

3. Rockwell International
   3370 Miraloma Ave.
   Anaheim, California 92803

   Contact: J. Doidge

4. Hughes Aircraft Company
   Culver City, California

   Contact: Dr. S. R. Scheele

5. Michelson Laboratory
   Naval Weapons Center
   China Lake, California 93555

   Contact: Dr. H. E. Bennett

6. Perkin-Elmer Corporation
   77 Danbury Road
   Wilton, Connecticut 06897

   Contact: Tony Ledger

7. Honeywell Systems and Research Center
   2600 Ridgeway Parkway
   Minneapolis, Minn. 55413

   Contact: Dr. R. Heinisch

Table 2. Percent Deviation between HRC and AEDC BRDF Data (10.6 μm)

Mirror No.	No. of Data Points	Average Deviation (percent)
B-1	8	- 6
B-2	12	34
B-3	12	22
G-1	12	58
G-2	12	67
G-3	12	36
A-2	7	- 3
A-5	8	7
A-6	7	4.3
A-7	6	-15
A-8	8	38
A-9	7	41
A-11	10	37
A-12	7	17

Average deviation for all mirrors = 24%

Table 3. Percent Deviation between RI and AEDC BRDF Data (10.6 μm)

Mirror No.	No. of Data Points	Average Deviation (percent)
B-1	11	- 41
B-2	11	104
A-5	3	- 4.3

Average deviation for all mirrors = 20%

Table 4. Percent Deviation between Aerospace and AEDC BRDF Data (10.6 μm)

Mirror No.	No. of Data Points	Average Deviation (percent)
B-1	11	40
B-2	11	12
B-3	11	-39
A-5	3	74
A-8	3	3

Average deviation for all mirrors = 30%

Table 5. Percent Deviation between Hughes and AEDC BRDF Data (10.6 μm)

Mirror No.	No. of Data Points	Average Deviation (Percent)
B-1	13	- 62
B-2	13	- 21
A-5	7	- 51
A-6	7	- 32
A-13	2	+ 54

Average deviation for all mirrors = -22%

Table 6. NWC Total Scatter Measurements (4 to 80 deg)

Sample	Wavelength	Total Scatter
Quartz	4762	6.98×10^{-4}
	5208	6.00×10^{-4}
	5682	6.00×10^{-4}
	6471	4.80×10^{-4}
B-1	4762	0.3
	5208	0.36
	5682	0.47
	6471	0.44
B-2	4762	0.19
	5208	0.22
	5682	0.28
	6471	0.24
A-13	4762	1.65×10^{-4}
	5208	8.40×10^{-5}
	5682	9.40×10^{-5}
	6471	9.40×10^{-5}

Table 7. Percent Deviation between HS&RC and AEDC BRDF Data (10.6 μm)

Mirror No.	No. of Data Points	Average Deviation (percent)
B-1	11	- 53
B-2	11	12
A-5	4	118
A-6	5	103

Average deviation for all mirrors = 45%

Table 8. Percent Deviation between Perkin-Elmer and AEDC BRDF Data (10.6 μm)

Mirror No.	No. of Data Points	Average Deviation (percent)
B-1	13	-51
B-2	13	+35

Average deviation for all mirrors = -8%

NOMENCLATURE

K	Radiometer sensitivity, $w/cm^2\ v$
P_i	Incident power on mirror, w
P_s	Scattered power from mirror surface, collected by radiometer, w
R	Radiometer responsivity, v/w
T	Transmission of attenuators
V_D	Detector voltage with radiometer viewing diffuse reflector, v
V_i	Detector voltage with radiometer viewing incident laser beam, v
V_r	Detector voltage with radiometer viewing reflected laser beam, v
V_s	Detector voltage from scattered radiation from mirror, v
θ	Radiometer angle measured from the specularly reflected beam, deg
ρ_D	Reflectivity of diffuse reflector
ρ_m	Reflectivity of test mirror
Ω	Radiometer acceptance solid angle, sr